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# Compilation of a glacier inventory for the western Himalayas from satellite data: methods, challenges, and results

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ABSTRACT

Due to their sensitive reaction to changes in climatic conditions, glaciers have been selected as an essential climate variable (ECV). Although a large amount of ice is located in the Himalayas, this region is yet only sparsely represented in global glacier databases. Accordingly, a sound and comprehensive change assessment or determination of water resources was not yet possible. In this study, we present a new glacier inventory for the western Himalayas, compiled from Landsat ETM+ scenes acquired between 2000 and 2002, coherence images from ALOS PALSAR image pairs, the SRTM digital elevation model (DEM) and the ASTER Global DEM (GDEM). Several specific challenges for glacier mapping were found in this region and addressed. They are related to debris cover, orographic clouds, locally variable snow conditions, and creeping permafrost features in cold-dry regions. Additional to seven topographic parameters that are obtained from the ASTER GDEM for each glacier, we also determined the relative amount of debris cover on the glacier surface. The inventory contains 11,400 glaciers larger than 0.02 km$^2$, which cover a total area of 9,310 km$^2$. Analysis of the inventory data revealed characteristic patterns of mean glacier elevation and relative debris cover amounts that might be related to the governing climatic conditions. The full dataset will be freely available in the GLIMS glacier database to foster further analyses and modeling of the glaciers in this region.


## 1. Introduction

The compilation of glacier inventories from automated multi-spectral classification of optical satellite data in combination with a digital elevation model (DEM) is meanwhile a well-established procedure (e.g. Andreassen et al., 2008; Bhambri & Bolch, 2009; Bolch et al., 2010; Paul & Kääb, 2005; Paul et al., 2009; Racoviteanu et al., 2008, 2009). There is also no question that a globally complete and detailed glacier inventory is urgently required (e.g. Cogley, 2009; GCOS, 2006; Ohmura, 2009) for a wide range of purposes, among others the modeling of the past and future contribution of glaciers to global sea-level rise (Hock et al., 2009; Kaser et al., 2006; Raper & Braithwaite, 2006), estimation of water resources and hydrological modeling on a regional scale (Huss, 2011; Kaser et al., 2010; Koboltschnig et al., 2008), as well as for accurate assessment of glacier changes (e.g. Paul et al., 2004). In particular the latter requires the availability of digital vector lines to refer glacier-specific changes to exactly the same entities.

For the heavily glacierized region of the Himalaya all of the above purposes apply, but little information is available in digital form for a sound change assessment of these glaciers over a large region (Bolch et al., 2012). This results in high uncertainties when local observations need to be generalized (Raina, 2009). Though strong efforts have been made recently to make glacier extents for the Himalaya region available, large parts are still missing in the glacier database of the Global Land Ice Measurements from Space (GLIMS) initiative (cf. Raup et al., 2007). The uncertainties and limited knowledge about the glacier in the Himalayas are obvious from recent debates in the media about the state and future developments of glaciers in this region (Cogley et al., 2010; Schiermeier, 2010). One of the regions with missing glacier outlines is the western Himalayan part of India, which is hence selected as a key region for this study. Glaciers were selected as Essential Climate Variables (ECVs) as they provide some of the clearest evidence of climate change and constitute key variables for early-detection strategies in global climate-related observations (GCOS, 2004). Investigations of glaciers are therefore especially important in regions with sparse climatic records or those where is still under debate whether climate change is occurring or not, such as the western Himalaya (Roy & Balling, 2005; Yadav et al., 2004).

A number of glaciological studies in this region are focusing on individual glaciers or on glacier inventories of smaller sub-basins (e.g., Bhambri et al., 2011; Kulkarni et al., 2007). Mass balance series exist for about a dozen of glaciers in the Indian Himalaya, many of them measured during the 70s to 90s (Raina, 2009). Extensive research has been performed in recent years on Chhota Shigri glacier (e.g. Hasnain et al., 2010; Kumar & Dobhal, 1997; Wagnon et al., 2007), which is part of the mass balance network of the World Glacier Monitoring Service (WGMS) since 2003 (WGMS, 2007). Due to the remoteness and difficult access to many of these glaciers, field observations are very

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laborious and time consuming. However, satellite data provide an ideal tool to investigate glaciers in this part of the world (Bhambri & Bolch, 2009; Racoviteanu et al., 2008). Besides mapping of glacier outlines, remote sensing techniques were also used for assessing mass balance, volumetric changes and mass loss of Himalayan glaciers (e.g. Berthier et al., 2007; Kulkarni et al., 2004; Matsuo & Heki, 2010). Both Racoviteanu et al. (2008) and Bhambri and Bolch (2009) identified the main challenges of glacier mapping in this region in the lack of a method to accurately delineate glaciers under debris cover, the lack of accurate digital elevation models (DEMs), and restrictions related to the use and export of topographic maps and scientific reports.

There are efforts made by Indian governmental institutions to complete a national glacier inventory (Raina & Srivastava, 2008; Sangewar & Shukla, 2009), which partly includes inventory work already compiled for several basins (e.g. Kaul, 1999; Vohra, 2010). These inventories are in tabular form, including topographic information such as minimum and maximum elevation, mean elevation of accumulation and ablation region, maximum glacier length, mean width, area, accumulation area ratio (AAR), and an estimation of mean depth and resulting glacier volume. Glacier outlines were obtained from topographic maps with additional information from aerial photography and satellite imagery if available. But as these outlines are not available in a digital form (Braithwaite, 2009), it is difficult to assess the quality and accuracy of these datasets. In many cases, reports and research as well as the source maps based on which these inventories were compiled are not published or even classified (Bhambri & Bolch, 2009). For the Himachal Pradesh and Uttaranchal states, digital glacier outlines were compiled by the International Center for Integrated Mountain Development (ICIMOD) using data from the Indian Remote Sensing Satellite series 1D (IRS1D) and topographic maps (ICIMOD, 2007). A new glacier inventory covering almost the entire Hindu-Kush, Karakoram, and Himalayas, has recently been compiled by ICIMOD (Bajracharya & Shresta, 2011), but the respective digital outlines are not yet available. Hence, an assessment of glacier changes based on the existing dataset is hardly possible as they differ regarding format, source data, acquisition method, analysts, and mapping purpose (cf. Racoviteanu et al., 2009). For the reasons above, any derived changes in glacier area might be more artificial rather than real (Bolch et al., 2012; Paul & Hendriks, 2010; Racoviteanu et al., 2009).

To overcome the major shortcomings of this situation, we here present a new digital glacier inventory that is derived from satellite data using semi-automated mapping techniques and now publically available. For the special challenges in this region such as heavily debris-covered glacier tongues combined with high solar elevation (reducing image contrast), frequent orographic clouds, seasonal snow, and glaciers ending in regions with permafrost, best effort approaches are presented to solve them. In particular, we apply a recently introduced new technique for improved delineation of debris-covered glaciers with coherence images from the ALOS PALSAR sensor (Atwood et al., 2010; Strozzi et al., 2010). The data analysis demonstrates the potential of the datasets and includes glacier parameters per river basin. By making the vector data sets of the resulting glacier outlines freely available through the GLIMS glacier database, more specific analyses or individual research questions can be performed and addressed. The focus of this study is thus on the methodological aspects of generating a state-of-the-art inventory for more than 10,000 glaciers in a region with challenging mapping conditions.

## 2. Study region and data

### 2.1. Extent of the glacier inventory

The study region is located in the western Himalayas and covers an area of more than 100,000 km$^2$. It reaches from the town of Kargil near Srinagar to the Tehri dam and the Alaknanda basin (Fig. 1). The northern limit is defined by the Indus, the southeastern limit by the Dhauli Ganga River. Several sub-basins of both the Indus (Jhelum, Chenab, Shyok, Ravi, Sutlej, and Gar Zangbo) and Ganges (Yamuna, Bhagirati, and Alaknanda) are included. The study region contains the parts of the Ladakh Range south of Indus, the Zanskar Range and parts of the Garhwal Himalaya.

Mid-latitude westerlies bring the main precipitation to the study region and can produce heavy snowfalls in winter (Böhner, 2006; Hatwar et al., 2005). This results in decreasing precipitation from the Indus-Ganges lowlands towards the Tibetan Plateau (Bookhagen & Burbank, 2006). The study region is located at the end of monsoonal conveyor belt, and is thus sensitive to the strength of the Indian summer monsoon (Bookhagen et al., 2005). In normal years, the influence of the monsoon is comparably low (Bolch et al., 2012), but in abnormal monsoon years such as 2002 and 2010 it can cause exceptionally strong rainfall events in the normally arid northern parts of the study region (Bookhagen et al., 2005; Juyal, 2010).

### 2.2. Satellite scenes

The USGS archive (http://glovis.usgs.org) was inspected to find Landsat scenes of the study region with as low snow and cloud cover as possible to be suitable for glacier mapping. We selected eight appropriate scenes from the Landsat ETM+ sensor acquired in 2000 (three scenes), 2001 (three) and 2002 (two) in good temporal agreement with the acquisition of the SRTM DEM. Due to complementary cloud cover, two scenes were chosen for path 147/row 37. Table 1 gives an overview on the satellite data used in this study. To facilitate the mapping of debris-covered glaciers parts, coherence images were created from four ALOS PALSAR image pairs (cf. Section 3.2). The sequential ALOS PALSAR scenes have been acquired from the ascending orbit in Fine-Beam Dual mode (FBD-HH/HV) with a 275 m baseline and a 46 day time interval during the snow-free period in 2007 (cf. 3.2. and Table 1).

On the pre-processing stage, we downloaded the selected Landsat ETM+ scenes and generated different color composites (RGB 321 for near true-color images and RGB 543 for discriminating clouds, ice, snow and debris). In the USGS archive, all scenes are in Universal Transverse Mercator (UTM) projection, with the scene center coordinates defining the zone. The scenes in our study region belong to UTM zones 43N and 44N and for practical purposes we decided to have the mosaiced inventory in a single UTM zone (43N).

### 2.3. Digital elevation models

A DEM of appropriate quality and resolution is required to separate individual glaciers along their drainage divides, and to derive specific topographic inventory parameters such as minimum, maximum, mean, and median elevation, mean slope, and mean aspect (Paul et al., 2009). For the study region, no local or national DEM with sufficient quality is publicly available. However, with the DEM from the Shuttle Radar Topography Mission (SRTM) and the ASTER GDEM, there are two elevation datasets available that cover almost the entire world, at least outside the polar regions, and that are accurate enough for compiling topographic glacier inventory data (Frey & Paul, 2012). The SRTM DEM was acquired using radar interferometry (InSAR) (Farr et al., 2007), which is subject to data voids in rugged high-mountain terrain due to radar shadow and layover effects. The Consultative Group for International Agriculture Research (CGIAR) compiled a void-free version (SRTM3v4) by interpolating the terrain in data voids based on information from other elevation datasets (Reuter et al., 2007). This void-free SRTM version has been used in numerous glaciological studies, mainly related to the assessment of ice volume variations with time (e.g. Berthier et al., 2007; Paul & Haeberli, 2008; Schiefer et al., 2007; Surazakov & Aizen, 2006). The dataset is available in 5 by 5 degree tiles; tile 'srtm_52_06' covers the entire study region and was used here. The ASTER GDEM was