Global and Planetary Change 118 (2014) 97–105

Contents lists available at ScienceDirect

Global and Planetary Change

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

Temporal and spatial changes in Western Himalayan firn line altitudes from 1998 to 2009

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ARTICLE INFO

Article history:
Received 7 May 2013
Received in revised form 18 February 2014
Accepted 7 March 2014
Available online 4 May 2014

Keywords:
firn line
temporal change
spatial change
Landsat
Western Himalaya

ABSTRACT

Understanding changes in glacier mass balance is important because it is indicative of changes in climate and the hydrologic cycle. The latter also has particular influence on people living near glaciers and/or glacier-fed rivers. The Western Himalayas remain one of the regions where recent changes in glacier mass balance are not well-known. The temporal and spatial changes in firn line altitudes are an indicator of equilibrium line altitudes and thus reflect changes in glacier mass balance. Here, we use Himalayan Landsat TM/ETM + data in July and August (the late summer melt season) to quantify changes in firn line altitudes from 1998 to 2009. We produced reflectance maps through radiometric calibration and atmospheric correction and use topographic correction to remove or reduce terrain or shadow effects. The real 'surface albedo' is obtained by narrowband-to-broadband (NTB) albedo conversion from the combined solar radiation. The firn line altitude was then extracted by combining the 'surface albedo' with pre-registered digital elevation model. The individual firn line altitude varies by region. The Western Himalayas display the largest range of firn line variability, where the firn line altitudes vary from 4840 m a.s.l. to 5770 m a.s.l. The individual glacier mean firn line altitude from 1998 to 2009 rose from 5072 ± 77 m a.s.l. to 5640 ± 74 m a.s.l. in the Western Himalayas. The mean firn line altitude increased from 1998 to 2009. The lowest mean recorded firn line altitude recorded was 5237 ± 166 m a.s.l. in 1998, whereas the highest was 5397 ± 135 m a.s.l. in 2000. We also observed a difference between the changes in fine line altitudes of northern and southern slopes of the western Himalayans, as the northern slope glaciers display a greater increase in firn line altitudes than the southern slope glaciers. In the southern slope, changes in firn line altitudes correlate with NCDC-NOAA temperature and precipitation data. This sustained increase of firn line altitudes and associated loss of glacier mass imply a persistent loss of stored freshwater in the Western Himalaya.

1. Introduction

Glaciers are a critical component of Earth's system and the current accelerated glacier retreats has significant impacts on both the environment and human well-being (WGMS, 2008). Glacier changes are key indicators of climatic changes as they show an enhanced and well recognizable reaction to even small climatic fluctuations, which results from their proximity to melting conditions (IPCC AR4, 2007). Glaciers can provide freshwater for agricultural and industrial production, yet they can also cause serious natural hazards, such as glacial debris flow and ice lake outburst flooding.

The Himalayan region contains permanent snowfields, which form the largest bodies of ice outside of polar ice caps (Kulkarni et al., 2002, 2005) and is a source of water for crucial rivers in Asia such as the Indus, Ganges and Brahmaputra. As a major regional water resource, the Himalayan glaciers consequently affect the South and Southeast Asian environment and the millions of people living there (Prasad et al., 2009; Vohra, 2010). Understanding changes in Himalayan glacial mass balance is essential to quantify the amount of freshwater stored in the glaciers. Determining changes in firn line altitudes using remote sensing techniques is an important means to assess potential mass balance changes over hundreds of kilometers across the Himalayas.

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http://dx.doi.org/10.1016/j.gloplacha.2014.03.012
0921-8181/

Firn lines are defined as the altitude at which snow remains on a glacier throughout the entire year (Seidel et al., 1997) and firn line altitude is an important parameter in predicting future changes in snow-covered area of the glaciers (Kaur et al., 2009). Local temperature, precipitation and topography influence the spatial distribution of firn lines (Kerr and Sugden, 1994) and the firn line depressions are linked to climatic perturbations (Kuhn, 1989; Atsumu et al., 1992). Firn line altitudes are also a viable alternative for the equilibrium line altitudes, and, consequently, for mass balance and climate reconstructions (McFadden et al., 2011).

Previous research has shown that the snowline can be obtained using a topographic map (Kurowski, 1891; Hess, 1904). However, the method is direct inference, or approximations valid for the long-term trend in firn line altitudes and is inappropriate for glaciers outside equilibrium (like those studied here). Optical remote sensing technology can be appropriate for shorter-term studies, and can be used to obtain data on firn line altitudes even in remote areas where ground observations are not available. In addition, statistical methods help classify firn line altitudes from remote sensing imagery. Seidel et al. (1997) defined the firn line as a belt of approximately 50% snow coverage and used Landsat TM and Systeme Probatoire d'Observation de la Terre (SPOT) data to evaluate its statistical objectivity. De Angelis et al. (2007) classified glaciers by calculating the Landsat TM4/TM5, TM2/TM5 and TM4/TM7 band ratios and thereby reducing the effects of shadows and the non-Lambertian nature of snow reflectance. In addition to the band ratio method, the snowline can also be obtained via a normalized difference snow index and reflectance map classification, where the reflectance map can be obtained by preprocessing the image by a supervised classification, an unsupervised classification, or decision tree methods (Heiskanen et al., 2003). In this paper, we present the temporal and spatial changes in firn line altitudes in the Western Himalayas, which are extracted from a time series of Landsat TM/ETM + and images acquired from 1998 to 2009 and SRTM DEM data. The National Climatic Data Center of the National Oceanic and Atmospheric Administration (NCDC-NOAA) meteorological data were used to study the response of changes in Western Himalayan firn lines altitude between 1998 and 2009 to climate.

2. Study site and data

2.1. Study site

The Himalayas are the world's highest mountains, encompassing areas of China, Pakistan, India, Nepal and Bhutan. The main Himalayan range runs west to east from Nanga Parbat (35°14′21″ N, 74°35′24″ E) in the western Kashmir region to Namjag Brawa (29°37′51″ N, 95°03′ 31″ E) in the eastern Tibet–Arunachal Pradesh region. The Himalayas, which are approximately 2400 km in length and vary between 240 and 330 km in width, are divided into three sections by individual mountains as the borders (1) Western Himalayas: from Nanga Parbat to the Naimona'nyi peak; (2) Middle Himalayas: from the Naimona'nyi peak to the Chomolhari peak; (3) Eastern Himalayas: from the Chomolhari peak to the Namcha Barwa (Zhang et al., 2012). The green triangle in Fig. 1 from west to east represents Nanga Parbat, Naimona'nyi peak, Chomolhari peak and Namcha Barwa, respectively.

The Himalayas contain one of the largest reservoirs of snow and ice outside of the polar regions. The first survey of the Himalayan glaciers was conducted in 1959 by von Wissman (1959), who identified a total ice cover of 33,200 km^2 which accounts for 17% of the Himalayan land surface. A more recent work by Qin (1999) identified that the glacierized area of the Himalayas is approximately 35,110 km^2, of which 8500 km^2 is located in the Indian Himalaya (Kaul, 1999). Precipitation in the Himalayas stems from both the continental westerlies and the South Asian monsoon. The westerlies sweep across central Asia before depositing their remaining water vapor near the Pamir and Karakoram. The North Indian Ocean branch of the southwest monsoon also delivers precipitation to the Western Himalaya, but this precipitation amount is less than the monsoonal precipitation transported to the Middle and Eastern Himalayas during May to September from water vapor originating in the eastern Indian Ocean. Glaciers tend to

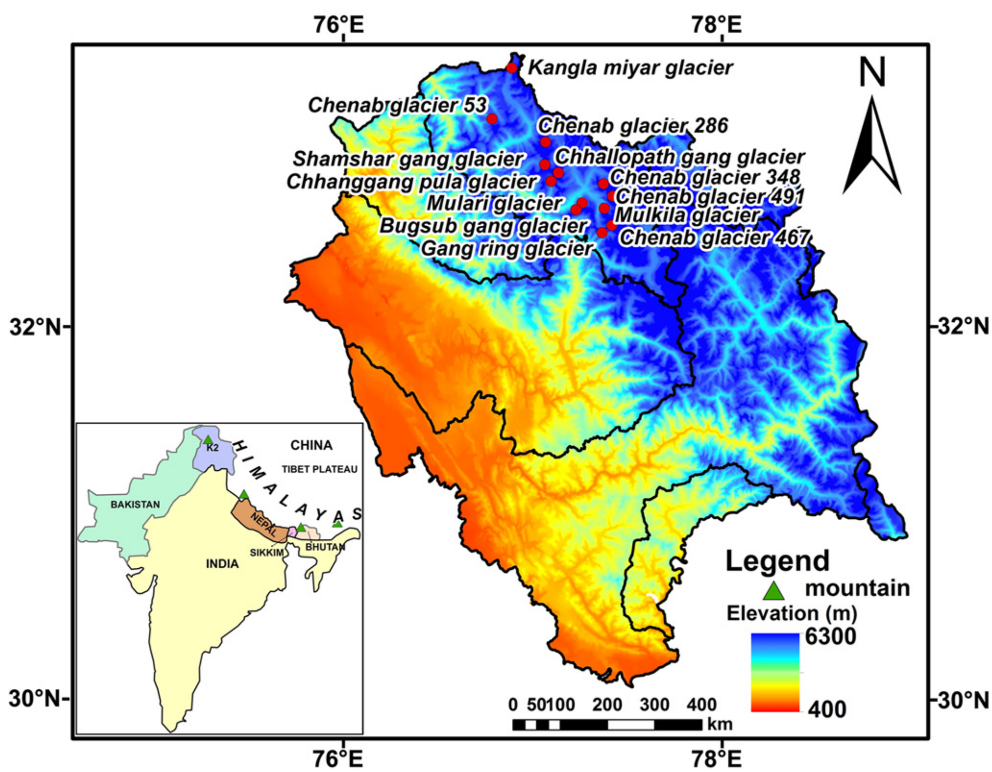

Fig. 1. Study area location and distribution of the selected glaciers. The red dot represents the selected glaciers, the green triangle represents Nanga Parbat, Naimona'nyi peak, Chomolhari peak and Namcha Barwa, respectively.