Article

The dynamic response of Kolohai Glacier to climate change

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Abstract
Glaciers are one of the important components of local, regional and continental water resource and are also key indicators of climate change. Glaciers provide a wealth of information about how climatic components of the earth have changed in the past. Changes in weather condition year after year cause variations in the amount of snow deposited on the glacier and in the amount of ice lost by melting of glacier. Interest in worldwide monitoring of glaciers has grown as rapid glacier recessions in many regions of the world have been evidenced. This further recognized need for a comprehensive assessment of the world's glaciers in driving efforts to devise and refine methods of extracting glacier information from satellite data. Due to adverse weather conditions, limited time is available in summer for detailed glacier studies. Remote sensing is of immense value as a mapping tool for measuring the spatial extent, mass balance and variations in the terminus of the glacier. Present study was carried out for Kolohai glacier of Lidder valley concentrated near Kolohai Mountain. This study is an attempt to reconstruct glacier fluctuations in response to climate changes through time series. A series of multidate imageries since 1992 to 2006 was used for mapping the changes in geometry and dynamics of glacier. Topographic maps, Landsat ETM, LISS-III imageries and high resolution DEM were used to conduct this study. The core of the methodology is to calculate the changes in areal extent and ELA variations of the glacier over the referenced time period and to determine the AAR of glacier. This was done by manual delineation, segment ratio of images to delineate changes. The study revealed that the Kolohai Glacier shows recession in terms of spatial extent, and variations in the terminus of the glacier in response to climate change.

Keywords glacier; ELA; AAR; sblation; retreat.

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1 Introduction

A glacier (Latin *glacies* meaning *ice)* is a large, slow moving mass of ice, formed from compacted layers of snow that slowly deforms and flows in response to gravity. Glacier is formed from precipitation in the form of snow and ice crystals. The upper part of a glacier that receives most of the snowfall is called the *accumulation zone*. In general, the accumulation zone accounts for 60-70% of the glacier's surface area. On the opposite end of the glacier, at its foot or terminal, is the *deposition* or *ablation zone*, where more ice is lost through melting than gained from snowfall and sediments are deposited. The altitude where the two zones meet is called the *equilibrium line* (also called the *snow line*). At this altitude, the amount of new snow gained by accumulation is equal to the amount of ice lost through ablation. Glaciers are one of the important components of local, regional and continental water resource. Changes in weather condition year after year (Zhang and Liu, 2012), cause variations in the amount of snow deposited on the glacier (accumulation) and the amount of ice lost by melting of glacier (ablation). Due to adverse weather conditions, limited time is available in summer for detailed glacier studies and hence ***Remote Sensing*** (Tahir et al., 2013) is of immense value as a mapping tool for glacier studies. Present study was carried out for ***Kolohai Glacier*** of Lidder valley concentrated near Kolohai Mountain. This study is an attempt to reconstruct the fluctuations in the glacier geometry as a response to climate changes through time series. A series of multi-date imageries was used for mapping the changes in geometry and dynamics of glacier. Methodology carried out for this includes manual delineation, segment ratio of images to delineate changes in its areal extent, determination of Equilibrium Line Altitude (ELA) in time for Kolohai glacier

2 Aims and Objectives

The main aim of this study was to find out the geometry of the Kolohai glacier like its area, width, shape and the glacier dynamics like ablation, Equilibrium line altitude (ELA), Area accumulation ratio (AAR) etc. In order to unveil the role of glaciers in the earth system it is necessary to understand the way in which their properties are organized in the modern time plane and also how they changed through the passage of time. Thus the glaciers are major players which help in unfolding the phenomenon of changing environment by providing a wealth of information about how climatic and other components of the earth system have changed in the past. In remote areas of rugged terrain the glaciers become inaccessible which restricts data collection in the normal course. Approaching glaciers becomes difficult in winter due to blocking of high passes, leading to these areas and hence limited time is available in summer which is not sufficient for detailed studies of all the glaciers in that particular region. Therefore for glaciological studies the glacier field surveys coupled with the remote sensing data are necessary to optimize the benefits. The easy availability of satellite remote sensing data of far-flung areas is of immense value for identifying various features of glaciers as glacier features show different spectral reflectance helping in characterizing and mapping them. This present study of the Kolohai glacier will prove to be of immense significance in understanding and assessing the changes in its extent, geometry change and re-constructing its last glacial maximum. Thorough monitoring of glacier geometry changes is helpful in global climate models and understands them to forecast future trend of water availability (Rignot et al., 2003). This study will enable us to understand glacier dynamics like ablation, equilibrium line altitude (ELA), accumulation area ratio (AAR) which is valuable parameters to monitor the state of glacier health.

3 Study Area

The present study deals with the reconstruction of Last Glacial Maximum (LGM) of Kolohai Glacier of Lidder Valley in Kashmir Himalaya (Fig. 1). The Lidder valley opens into southeastern corner of Kashmir valley giving passage to a river of same name and is situated between geographical co-ordinates of $33^{o}43'$ - $34^{o}15'$ N latitude and 75^{0} 05′ - 75^{0} 32′ E longitude. The Glaciers in the Lidder valley are presently confined along the northern ridge of the east and west Lidder valley. Kolohai Glacier, located at an altitude of 3690 m, is the largest glacier among west Lidder valley glaciers which are concentrated near Kolohai Mountain. Lidder is one of important tributaries of river Jhelum, formed by two mountain torrents (east and west Lidder). The first mountain torrents rise from Sheshnag and carving a deep gorge round Pisu hills, flows past Chandanwari to Pahalgam. Near Pahalgam, a second torrent rising from the south of Kolohai glacier receives a tributary from the Sanasar lake near Kolohai valley enters it, the whole volume of water swelling and flowing with rapidly to join first torrent at Pahalgam. It plays an important role in hydrological and socioeconomic system of local communities. Lidder (yellow river) is known for its scenic value and plays very important role in promoting tourism in Jammu and Kashmir.

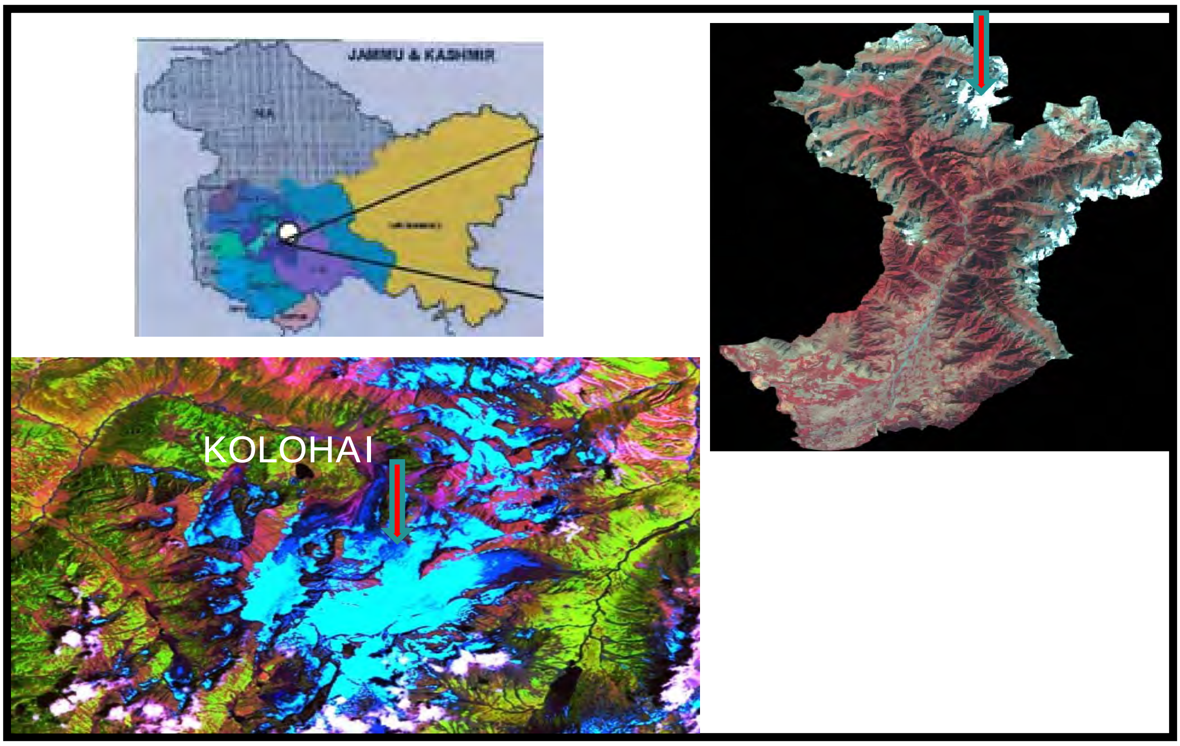

Fig. 1 The location of the Kolohai Glacier in the Lidder valley of Kashmir Himalaya, India.

4 Methodology

The data sets used were topographic maps, Landsat – ETM (1999), Landsat – ETM (2001), LISS III (2006) and DEM (90 m) The topographic maps were used in the rectifying and entailing the determination of locations of the features that are easily recognized in both a satellite image and corresponding cartographic coordinate system. First, extensive pre-processing has been performed to enhance comparability of multi-date images which includes the topographic corrections, mosaic creation and multi-date radiance normalization. Since visual analysis of multi-date images has the capacity to overcome the complexity of land cover change the multi-date images and the topographic maps were visually analyzed (visual interpretation) by incorporating key elements such as texture, shape, size and patterns.

5 Results and Discussion

The study revealed that the Kolohai glacier shows recession in terms of spatial extent and variations in the terminus of the glacier in response to climate change (Fig. 2). From the comparison of the calculated glacier area from the multi-series data it was observed that the glacier extent has drastically decreased with the passage of time. Further the glacier has retreated from 13.87 km^2 to 11.24 km^2 during time series between1976 to 2006 (Table 1 and Fig. 3) while the terminus position has also changed from 3522 m to 3655m from 1976 to 2006 respectively. The snout has also narrowed from 560.76m to 116.86m leaving behind end and lateral moraines (Fig. 3). In 2006 the ELA of Kolohai glacier lies within 4594m altitude while AAR is 0.59 (Table 2).

The occurrence of glacier is related to climatic conditions and they form in those parts of the world where the rate of accumulation is greater than melting of snow under lower temperature. In mountainous areas glaciers are located above the snowline and they can be found virtually at any altitude where solid precipitation is sufficiently large to promote permanent ice cover wherein topographic and climatic factors are favourable for deposition and survival of snow. Globally it has been found that the permanent snowline lies at sea level at poles, 1200 m for Scandinavia, 2500-3000 m for Alps and 5000-6000 m for Equatorial locations (Upadhyay and Bahadur, 1982). In Himalayan regions glaciers are generally found at altitude of above 4000m. Although remote sensing has served as an efficient method of gathering data about glaciers since its emergence the recent advent of Geographic Information Systems (GIS) and Global Positioning Systems (GPS) has been found most useful to analyze the acquired data in the effective monitoring and mapping of temporal dynamics of the glaciers. The glacial features, identifiable from aerial photographs and satellite imageries, include spatial extent, transient snowline, equilibrium line elevation, accumulation and ablation zones and differentiation of ice/snow. Digital image processing (e.g., image enhancement, spectral ratioing and automatic classification) improves the ease and accuracy of mapping these parameters. The traditional visible light and infrared remote sensing of two-dimensional glacier distribution has been extended to three-dimensional volume estimation and dynamic monitoring using radar imageries and GPS. The emergence of new satellite images will make remote sensing of glaciology more predictive, more global and towards longer terms.

Table 1 Recession of Kolohai glacier area.

Year	Area (km^2)
1976	13.87
1999	12.98
2001	11.79
2006	11.24
Average Recession 0.65 km^2/year	

Table 2 ELA and AAR values.

Year	**ELA**	**AAR**
2001	4205	0.57
2006	4594	0.59

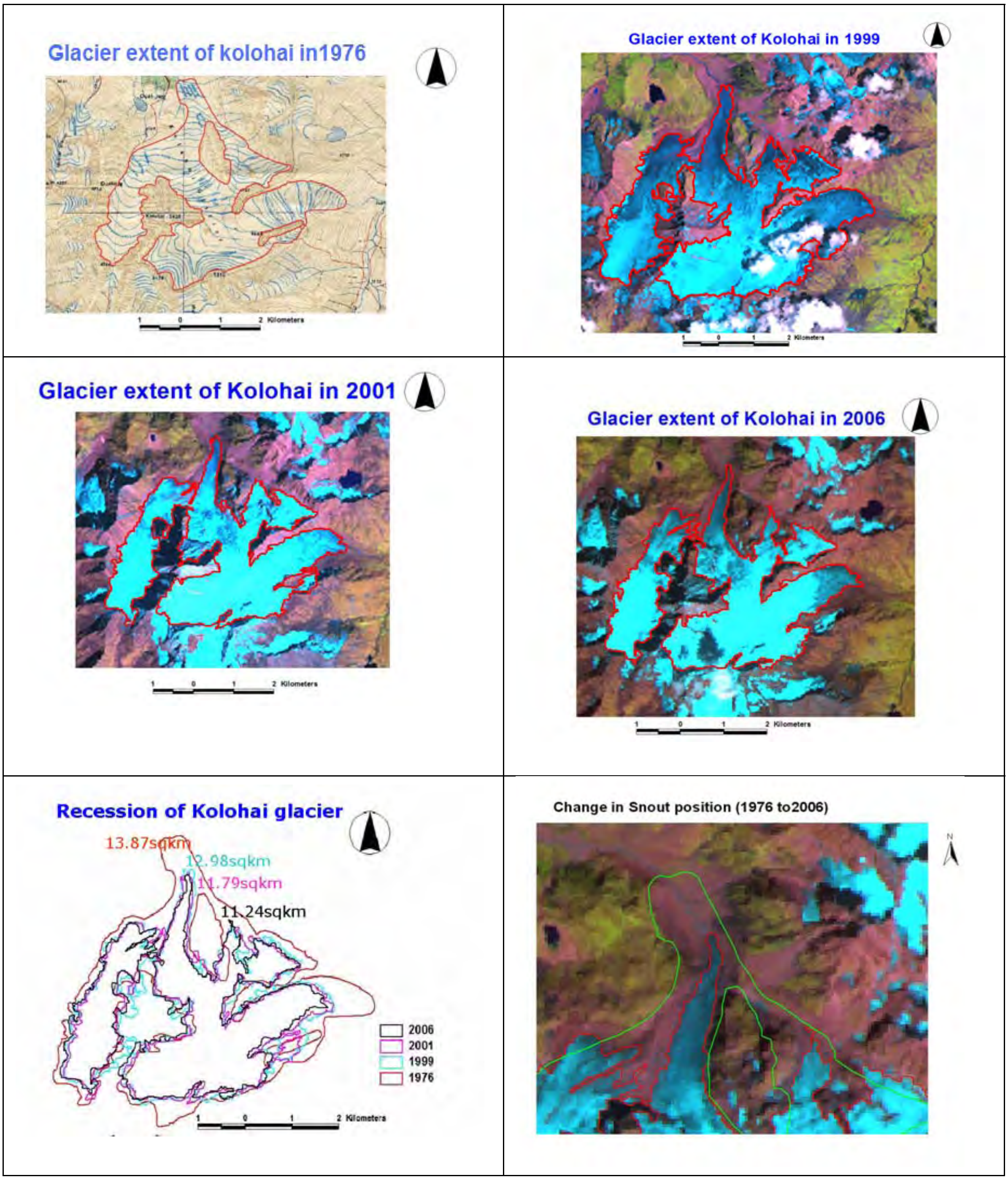

Fig. 2 Recession of the Kolohai glacier and the changes in the snout position since 1976 to 2006.

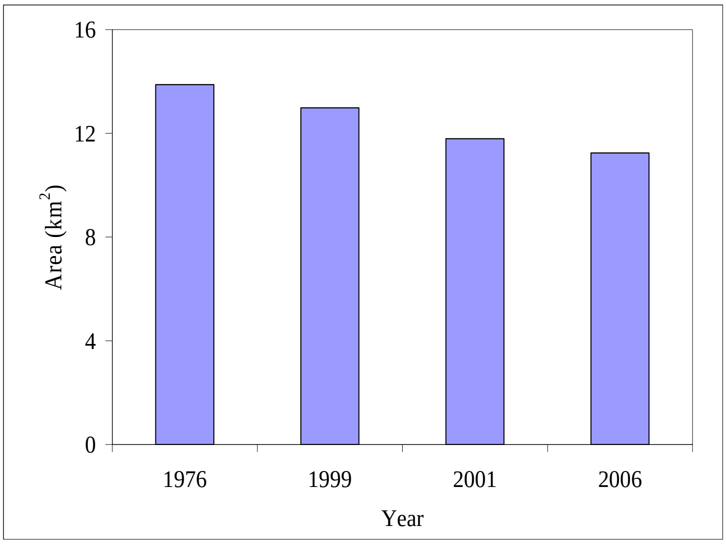

Fig. 3 Recession of Kolohai glacier area in terms of area.

6 Conclusions

Mass balance for non-calving glaciers is the difference between snow accumulation on a glacier and snow and ice loss from the glacier. Monitoring glacier mass balance is important for understanding and predicting the response of glaciers to climate change and resulting impacts on sea level change, watershed hydrology, and glacier-related hazards. However, direct measurements are scarce (Dyurgerov, 2002) since traditional mass balance measurements are highly time- and labour-consuming, and glaciers tend to be located in remote areas. Hence ELA and AAR have been used to understand the glacier mass Dyurgerov (1996). The mass balance studies carried out for the Kolohai glacier by using the remote sensing data between years 1976 and 2006 revealed considerable recession in its spatial extent. The retreat is from 13.87 km^2 in 1976 to 11.24 km^2 in 2006. The values of ELA and AAR indicate negative mass balance of the Kolohai glacier.

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