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Glacier and Lake Areas and Snowlines Over Past Two Decades: Status of Alaknanda Basin

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ABSTRACT

We use satellite remote sensing and a DEM to determine the snowline altitude of the Alaknanda basin. One hundred and six glaciers were monitored, indicating that the Alaknanda basin has decreased in area by 58% over the period 1990–2014. It is observed that snowline altitude is generally higher during 2010/11 than 2012/13 and 2013/14. The lowest snowline altitudes were observed to be 3335 m a.s.l. in March 2011 and 3300 m a.s.l. in February of 2014. Our detailed data on glacial and lake areas over 30 years provide an important spatiotemporal assessment of climate variability in this area. These data can be integrated into further studies to analyze inter-annual glacial and lake area changes and assess hydrological dependence and consequences for downstream populations.

Keywords: accumulation, climate, snow

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INTRODUCTION

Glacier changes are excellent indicators of climate change, as small climatic variations can produce rapid changes (e.g. Houghton, 2001; Haeberli, 2004; Soruco and others, 2009; IPCC, 2007; Vuille and others, 2008a; Rabatel and others, 2013). The Himalayan region has permanent snowfields, and in winter most high altitude regions experience snowfall. During summer, snowmelt is the major runoff for many rivers originating from the Himalaya, including those that are key elements of agricultural systems of South Asia (Kumar and others, 2005). Changes in glacier melt amount and patterns, along with other changes in high-altitude hydrology, will affect agriculture production across the region. Many Himalayan glaciers are retreating faster than the global average (Dyurgerov and Meier, 2005) and are thinning by 0.3-1 m a^{-1} (ICIMOD, 2009).

The rate of retreat for the Gangotri Glacier over the past three decades has been more than three times the rate during the preceding 200 years. In the central Himalayas, glacial melt associated with climate change has led to the formation of glacial lakes in open areas behind exposed end moraines, causing great concern.

Due to rapid recession of glaciers, a number of catastrophic effects such as glacial lake outburst floods (WWF, 2005; Mool and others, 2007) and water scarcity in the upper Himalayan rivers have been reported (Kulkarni and others, 2002; 2007). Mapping and monitoring of seasonal snow cover and snowline is a challenging task in the Himalaya, and remote sensing has emerged as a useful technique for this work (Hall and others, 2005; Rathore and others 2015).

STUDY AREA

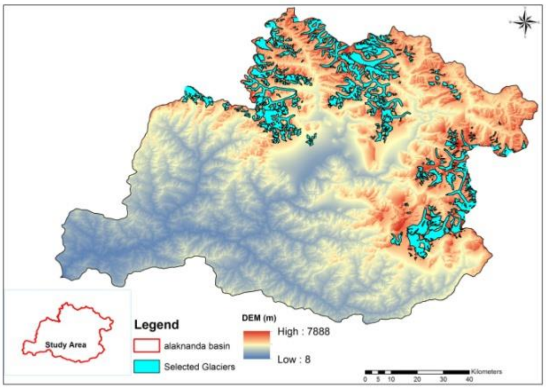
The glaciated area in the Alaknanda Basin extends from 30º 15' N to 31º 04' N latitude and 79° 13' E to 80° 13' E longitude. There are 540 glaciers in the basin, covering an area of 1675 km^2, with ice reserves of 191 km^3. The largest glaciers in this basin are the Satopanth and Bhagirath Kharak, with length > 19 km and area coverage, 98 km^2. Satopanth and Bhagirathi Kharak glaciers are two main valley glaciers and are the main sources feeding the Alaknanda River. These glaciers originate from the peaks of the Chaukhamba and Badrinath ranges, which separate them from the Gangotri group of glaciers.

The computation of glacier changes for all glaciers in the Alaknanda region presents significant difficulties because of snow cover, cloud in images, or errors in the original topographic maps. In this study, 119 glaciers with combined area, 393 km^2, and including some heavily debris-covered glaciers (Fig.1) are investigated, As glacier area change, lake area change and snowline change research in this region are rare, this work is significant.

DATA AND METHODS

DATA

Topographic maps at scales of 1:50,000 are utilised from the Survey of India. The main image sources were Landsat TM available from USGS (United State Geological Survey, (http://glovis.usgs.gov/) and were orthorectified automatically using USGS Shuttle Radar Topography Mission (SRTM) DEM data. The scenes without cloud and with little seasonal snow were selected for glacial extent, and were acquired in 1990 (145 path and 39 row) along with LISS III images from 2001, 2005, 2010 and 2014. In this study LISS IV (5.8 m) Cartosat Merged data (2.5 m), LISS III (23.5 m) and Landsat TM (30 m) are also used for glacial lake extent. Snowline mapping was done by analysing AWiFS data over the period 2010 to 2014. Images covering July–September were selected, because during this period snow cover is at its minimum and glaciers are fully exposed. Elevation values (m) were derived from a SRTM-DEM.



SRTM

During the SRTM in February 2000, elevation data covering ~80% of Earth's surface became available. Freely available SRTM DEM (the fourth version) data, combined with elevation data from another time point can provide an opportunity to calculate changes in glacier surface elevation with nominal vertical accuracy of 6 m relatively and 16 m absolutely; the nominal horizontal accuracy is 15 m relatively and 20 m absolutely (Rabus and others, 2003).

Figure 1. Location of Alaknanda Basin Glaciers

Here we utilized a 90 m resolution SRTM DEM from 2000 and the 1962 elevation data from topographic maps of glacier thickness change. The geodetic reference for SRTM data is the World Geodetic System 1984 (WGS84)

METHODS

B.I Data preprocessing: Geocorrections and co-registration were conducted using Arc GIS software for all images. Clearly distinguishable terrain features from topographic maps were used as reference to register the other images. All images and maps were presented in the Universal Transverse Mercator (UTM) system referenced to the World Geodetic System of 1984 (WGS84).

B.II Glacier area extraction: Glacier outlines for the 1962 period were extracted from topographic maps using ArcGIS 10.1. For the 1990 and 2014 periods, a preliminary glacier boundary was automatically generated from the band ratio method. This approach was automatically applied using the band ratio of TM4/ TM5 on Landsat images and then complemented with visual interpretation to glacier outlines (Bayer and others, 1994; Jacobs and others, 1997; Bloch 2007). Glacier polygons then derived from the ratio method were visually checked for gross errors and were manually improved where necessary.

Glacier elevation change extraction: Glacier boundaries were delineated using topographic maps and digitized using GIS techniques. On satellite images glacial boundaries were mapped using standard combinations of bands. An image enhancement technique was used to enhance the difference between glacial and nonglacial areas. Ancillary data, e.g. basin boundaries, rivers, glacier boundaries, and drainage and spatial frame work parameters are from the 1: 50,000 scale Survey of India topographic map frames, provided by the Natural Resources Database (NRDB). Elevation values (m) were derived from aster-DEM.

Lake area extraction: The objective of lake extraction is to correct and refine glacial mapping by outlining proglacial lakes in the imagery. Lakes provide a unique signature on satellite images, mainly due to the contrasting signature of associated land cover classes viz. rocks, scree, snow etc. Most of the lakes have very clear water, thus appear dark in satellite images due to very low reflectance. Data acquired when the water is in liquid state facilitate easy delineation of lake boundaries. Two seasons of satellite data capture the freezing and melting scenario of lakes and enhance identification accuracy. To increase the classification accuracy, various indices were generated from the spectral bands:

1) Normalised Difference Water Index (NDWI) = (Green-NIR) / (Green + NIR)
2) Normalised Difference Vegetation Index (NDVI) = (NIR - Red) / (NIR + Red)
3) Normalised Difference Pond Index (NDPI) = (MIR – Green / MIR + Green)

Suitable indices were used to enhance the water body and to discriminate snow from cloud. Elevation contours generated from the SRTM data were used to delineate the wetlands above 3000 m, designated as HAWs. Lake statistics, viz. total number, size category, altitude distribution pattern, area, perimeter etc. were generated from the database. A typical map output at SOI topographic map level shows the high altitude lakes and other wetland classes.

Snowline extraction

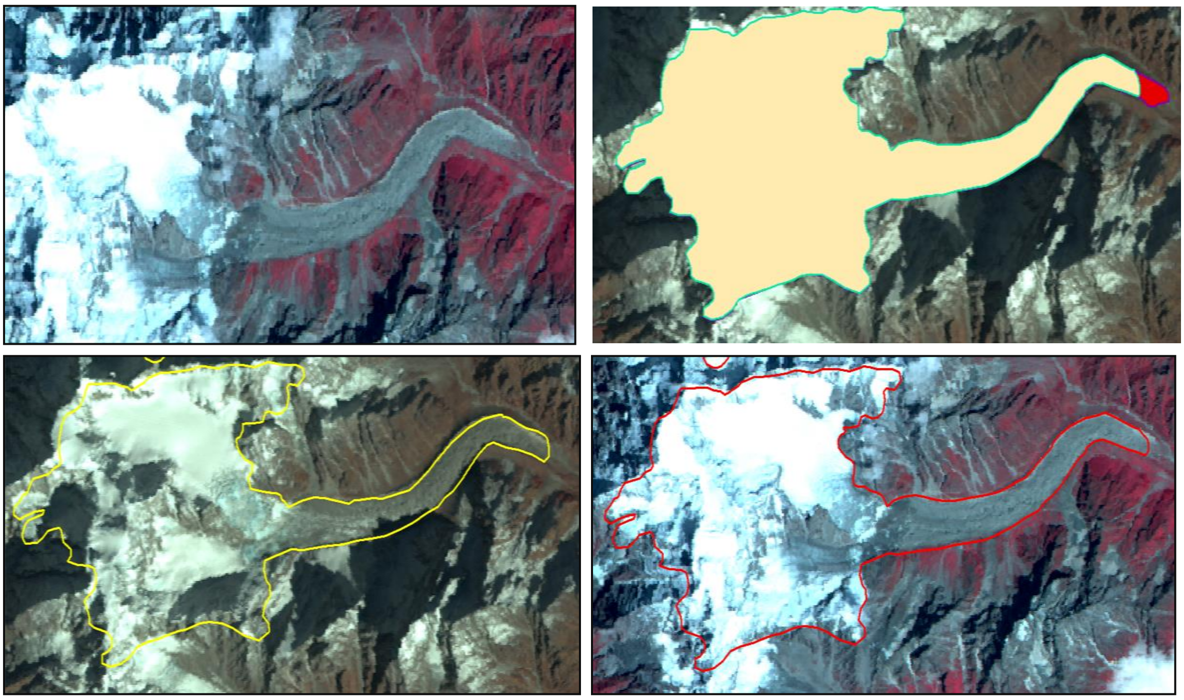
The term 'snowline' has different meanings, depending on the context in which it is used. The transient snowline refers to the boundary between the snow covered surface and a bare surface at a given time (Østrem, 1974). In our study we follow a 3-step methodology to determine snowline (Kaur, 2010), using

AWiFS data. After 2010, snow cover was generated using AWiFS data. All usable images were converted to reflectance and calibrated to the reflectance of the base image. Snowline is determined using hypsography derived from a DEM and from snow-cover maps, by a normalized-difference snow index (NDSI) technique. After filtering, outlines were converted to points and ASTER DEM values at those points extracted, to determine snowline elevation.

RESULTS AND DISSCUSSIONS

A. Glacier Extent in Alaknanda Basin

The approach adopted here is based on areal extent measurements using two time satellite data. Measurements of changes in extent of glaciers were interpreted using satellite images only. The satellite images used as reference are Landsat TM images of 15 November 1990 and recent images of 9 October 2014. Digital databases for the areal extent of individual glaciers of each basin have been created in a GIS environment. Landsat images available for 1990 covering this basin show that most glaciers are not snow covered. One hundred and six glaciers were monitored and results indicate that the Alaknanda Basin has decreased in area by 58% over the period 1990-2014. When glacier extents were compared using satellite images available from 1990 and 2014 we find there is a 68% loss of total surface area. The glacier areas in 1990 and 2014 are 393 km^2 and 335 km^2 respectively for the 106 glaciers. Each of the glacierized regions within the Alaknanda Basin has declined at a different rate. For the individual glacierized regions we report mostly decreasing decline rates during 1990-2014, shown in Figure 2 and Table 1. We also note that on average, smaller glaciers have higher decline rates than larger glaciers.



Snout in 1990 (Landsat – TM)   Snout in 2014 (LISS III)

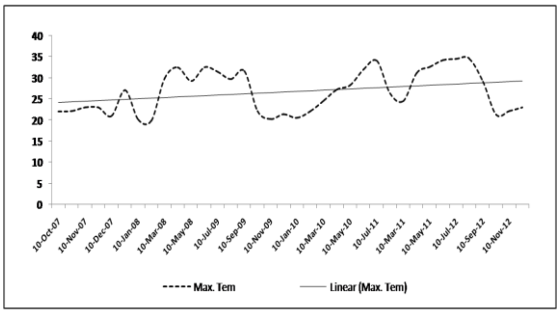
Fig.1. Area change between 1990 and 2014

Himalayan region for the past century show an increase in temperature of around 1.6^0 C/100 years, with winters warming at faster rate (Bhutiyani et al., 2007). Outside the western Himalaya, Shrestha and others in 1999 found that maximum temperature trends increased, ranging from 0.6^{0}c to 1.2^{0}C per year, this indicates that temperature increase might be major cause of the glacier recession. The altitude of the accumulation zone is another key factor which influences the ablation rate of glaciers. Generally it was observed that Alaknanda glaciers are located at higher ones Table 1. The area and length of six glaciers in 2014

	1990		2014	
CGI Number	**Area km^2**	**Length km**	**Area km^2**	**Length km**
53N5-016	3.34	35.35	3.30	34.61
53N5-015	2.72	40.46	1.6	39.68
53N5-013	2.08	8.52	2.07	7.94
53N9-018	4.71	14.09	4.68	13.8
53N9-013	5.33	17.56	5.31	17.84
53N10-008	1.83	9.97	1.82	9.65

B. Snow Line Mapping

Remote sensing techniques have been used extensively for snow-cover monitoring in the Himalayan region, with the help of numerous satellite sensors (Kulkarni and Rathore, 2003). Snow cover products were made for each sub basin boundary of Alaknanda, and snow areal extent was estimated. Sub-basin altitude zones were determined by overlaying the contours derived from Aster DEM. The DEM product has 90 m resolution. The DEM is converted into a contour map at 1000 m interval using ARC GIS. Hypsographic curves were prepared to estimate area/altitude distribution for each sub-basin. The curves were also used to estimate snow line altitude based on the snow cover extent. Ten daily products were converted to polygon layer using raster to vector conversion. GIS intersection analysis was used between the snow cover products and altitude zones to derive snow area within each altitude zone.



Snow cover area within each altitude zone was estimated using GIS for comparative analysis to understand the effect of altitude (varying from 500 to 7000 m) on accumulation and ablation pattern at sub-basin scale. TM data for 1990 were used to geo-reference AWiFS images. Overall snow cover in 2010/11 is less than that of 2012/13 and 2013/14 (Table 2). The melt season begins in March and continues until June for both years. There is a similar ablation pattern, ablation being higher in 2010/11 than in 2012/13 and 2013/14. The mean snow cover for June 2011 is 64% less than in June 2014 (Rathore and others, 2015).

The snow line altitude is generally higher during 2010/11 than 2012/13 and 2013/14. The lowest snowline altitude was observed to be 3335 m a.s.l. in March 2011 and 3300 m a.s.l. in February 2014. The snowfall is generally less during 2010/2011 than during 2013/2014.

Table 2. *Monthly average snowfall (m) at Chopta in the Alaknanda Basin*

	2010/11	2013/14
Oct	2.4	3.2
Nov	1.9	3.4
Dec	2.2	4.05
Jan	2.2	3.13
Feb	3.8	5.8
Mar	4.1	4.6
Apr	4.5	4.68
May	3.63	4
June	2.69	6.5

The lower snowline elevation corresponds to the greater initial snow accumulation and the higher elevation corresponds to the lower initial snow accumulation. Comparison of the snowfall data of Table 3 with the altitude data of Figure 3 supports the applicability of our methods of determining snowline altitude. Snowfall is generally less during 2010/11 than during 2012/13 and 2013/14.

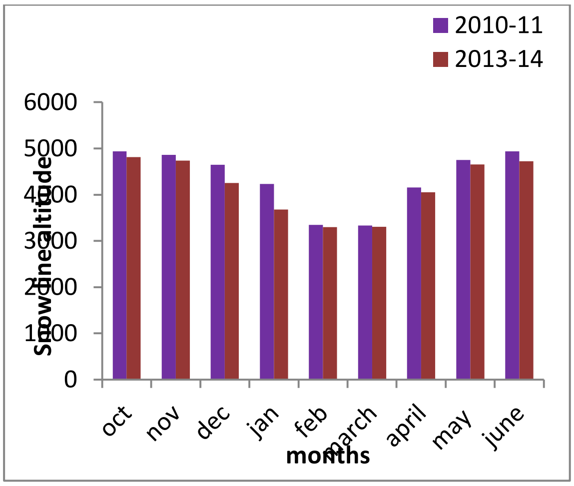


Fig. 3. *Snowline altitude (m) from October 2010 to June 2014*

Air temperature data of Dehradun (www.TuTiempo.net) from 2007 to 2012 is depicted in figure 4, which shows subtle increasing trends of maximum 10 daily average temperature. Rise in temperature and reduced snow cover were observed in April to June 2011 which also gets reflected in high snow line for the year 2011

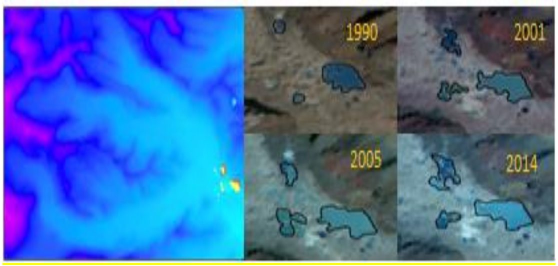


Fig. 4. *Maximum air temperature (10 day average) at Dehradun from 2007 to 20012*

C. Fig 2 Lake Area Changes

No previous studies exist of proglacial and glacier-fed lake area changes in Alaknanda Basin, and this is the first regional study summarizing lake area change derived from satellite imagery. The majority of lakes in this region that we tracked have been small, with area <0.22 km^2. Smaller lakes have larger errors associated with their measurements, and data for many of our identified lakes fluctuate widely. This is likely a result of unstable lake areas, classification methodology and the fact that many images require different thresholds to visually outline the same lake area.

Table 3. *Glacial lake area from 1990 to 2014*

Year	1990	2001	2005	2015
Area (km^2)	0.018	0.023	0.23	0.23
Change (1990-2014)	Total change of 0.2122			

These factors make interpreting a temporal signal difficult. In this study we focus on the lakes that are not affected by classification threshold and size limitations. We observed the rapid development of ten proglacial lakes since 1990, which previously did not exist. The development of these lakes reflects glacial retreat in this region, with the period 1990-2014 showing greater lake growth than during the previous 3 decades. First observed in Lake ID: 2, Figure 3 illustrates the growth of a lake by 0.02 km^2 in the three decades between 1990 and 2014. This lake appears to have seen the majority of its growth during the mid-late 1920s. The coincidence in timing with other lake area increases and the increase in glacial melt rates is likely a regional climatic signal. We also notice the development of many smaller lakes in this region during 1990-2014, indicating the likelihood that this area became much wetter. We conclude that this lake level change is due to a combination of enhanced glacial permafrost melting at high elevation and more precipitation at lower elevation. The timing of this lake area increase is similar to that of other lake area observations (Ids: 3, 5, 10, 11, 13, 15; Fig. 3). Similarly, some of the lake areas decreased (Ids 4, 7, 8, 9, 12; Fig. 4). In order to put our analysis into an expanded spatial context, we show the lake area trends for 37 identified lakes. Using the SRTM DEM, we delineated the watershed for each lake and identified whether they were connected to glacial regions or not. The most recent lake area was normalized against the earliest lake area (using Landsat TM images only); values > 1 indicate growing regions and <1, decreasing regions. To summarize, proglacial lakes are in good spatial and temporal agreement with glacial melting.

Fig.5. *Ground photograph of glacial lake in the Alaknanda basin*

Most lakes observed in the study region are small, yet may be dangerous to downstream communities. In 2013 Chorabari Lake burst, causing flooding of the Saraswati and Mandakini rivers and large-scale devastation in the lower regions of the valley (Dobhal, 2013). Case studies on such natural hazards, including GLOFs, are widely documented in the study area, and these hazards continue to exist. (Hegglin and Huggel, 2008).

CONCLUSION

The following conclusions have been drawn from this study.

I. A total of 106 number of glaciers were mapped in Alaknanda basin. It was observed that smaller glaciers have higher decline rates than larger glaciers.
II. Approximately 2% snowfall increased in the Alaknanda basin in year 2010/11 to 2013/14. However, the increase in snow cover observed was found to be statistically insignificant.
III. Variation in snow cover changes has been observed higher in accumulation period than in ablation period in Alaknanda basin. Snow line reaches its lower altitude during the accumulation period where fluctuations in temperature are frequent.

Most of glacier lakes observed in the study region are small, yet may be dangerous to downstream communities.

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