A Study of the Gangotri Glacier Retreat in the Himalayas using Landsat Satellite Images

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Abstract
The retreat of glaciers is an indicator of climate change, and is rapid in the Himalayas. Multi-temporal satellite images are ideal for studying changes in glaciers in the rugged Himalayan landscape. In this study, Landsat (MSS, TM, ETM+) images were used to locate the position of the ice wall of the Gangotri glacier in1976, 1979, 1990, 1999, 2006 and 2009. The results of image interpretations indicated that between November 1976 and February 2009, there was an average annual retreat of 22m in the ice wall's position. The straight-line distance between the 1979 position and the 2009 position of the ice wall was about 700m. The cave of the glacier also changed its position longitudinally a few times over the study period. Fluctuations in the average monthly temperature and precipitation in the region during monsoon and winter seasons could have influenced the rate of recession of the Gangotri glacier.

1. Introduction

Glaciers are the key indicators for assessing climate change in remote mountain areas where climate stations are rare or nonexistent (Bolch et al., 2008 and Ageta and Kadota, 1992). Retreats of glaciers are rapid in the Himalayas, and they are expected to continue in the future (Ageta and Kadota, 1992, Nakawo et al., 1997 and Hasnain, 1999). Himalayan glaciers are "summer accumulation types" – i.e., they depend on summer monsoonal precipitation and cool summer temperatures (Ageta and Higuchi, 1984). Monsoonal precipitation on the glacier's surface increases albedo and reduces ice and snow melting (Wesseles et al., 1993). About 75 percent of discharges in the Himalayan rivers occur from May to September due to a rise in atmospheric temperature and precipitation (Collins and Hasnain, 1995). Any variations, therefore, in monsoonal temperature and precipitation will influence the conditions of the glaciers in the Himalayas. Hence, monitoring Himalayan glaciers has significant importance in understanding global climate change. Other reasons to justify the continuous monitoring of these glaciers are that the Himalayan glaciers are a fresh water source for millions of people (Bandyopadhyay and Gyawali, 1994), and a probable source of devastation by floods from glacial lake outburst (Bajracharya and Mool, 2009). Due to the rugged, inaccessible terrain and delicate political situation, field studies are often difficult or not possible in certain parts of the Himalayas. Increased availability of high temporal and spatial resolution images from remote sensing satellites has helped to measure the glaciers' parameters over larger areas and through longer time spans in these challenging Himalayan landscapes (Bolch et al., 2008 and Kargel et al., 2005).

The Himalayan mountain ranges have approximately 5,218 glaciers covering 33,200 km^2 (Flint, 1971). In addition, 30 to 40 percent of the Himalayan area has seasonal snow cover. Previous studies in the Himalayas and elsewhere have measured glacial recession (Kadota et al., 2000, Fujita et al., 2001, Kargel et al., 2005 and Ren et al., 2006). These studies show that Himalayan glaciers have been in a state of general retreat since 1850 (Mayewski and Jeschke, 1979). More recently, Landsat and ASTER satellite images have been used successfully to study glacial retreat (Bolch and Kamp, 2006). In this regard, the Global Land Ice Measurements from Space (GLIMS) program is collecting satellite images of world glaciers, analyzing glacier changes, and assessing the causes and implications of those changes (Kargel et al., 2005). This study used Landsat satellite data to assess the planimetric changes in the Gangotri glacier. Gangotri has been receding since 1780, but its retreat quickened after 1971 (Kargel, 2004). Various studies have measured the amount of retreat of the Gangotri glacier (Mayewski and Jeschke1979, Kulakarni and Alex 2003 and Dobhal et al., 2004). Vohra (1981) observed a retreat of about 615m between 1935 and 1976, and Mukherjee and Sangewar (2001) found an 800m retreat between 1935–1997; Naithani et al., (2001) found a 76m retreat between 1996–1999. It has been ten years since the last known study that reported the

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This study extends the current knowledge of the Gangotri glacier retreat up to the year 2009.

2. Study Area and Methods

The Gangotri glacier (Figure 1) is about 30 km long with its width varying from 0.5 to 2.5 km. It flows in a NW direction. This glacier is bound between 30°43′22″–30°55′49″ N and 79°4′41″–79°16′34″ E, and the elevation ranges from 4120 to 7000 MSL. The Gangotri glacier comprises three main tributaries: Raktvarn (15.90 km), Chaturangi (22.45 km), and Kirti (11.05 km). It is the second largest glacier in the Himalayan region in India (Naithani et al., 2001). To measure the planimetric changes in Gangotri glacier, this study used Landsat satellite data from 1976 to 2009. Since the Himalayan glaciers are dependent on summer monsoonal precipitation and cool summer temperatures, Landsat images used in the study were acquired during winter (November to February). The data sets used include Landsat MSS, TM and ETM +. Dates of acquisition of these images are in Table 1. All images were collected from the United States Geological Survey (USGS) Earthexplorer (www.earthexplorer.usgs.gov/) web portal. These images were already georeferenced and were in UTM zone 44, WGS 84 datum.

Table 1: Satellite images used in the study

Date	Satellite
Nov, 19, 1976	Landsat - MSS
Jan, 12, 1979	Landsat - MSS
Nov, 15, 1990	Landsat - TM
Oct, 15, 1999	Landsat - TM
Nov, 03, 2006	Landsat - ETM+
Feb, 28, 2009	Landsat - TM

In order to correct the minor differences in image registration and to improve the accuracy, all images were geocorrected again with respect to 2009 Landsat TM image. The RMS errors were less than 5 meters in all cases. The terminus of the Gangotri glacier has an ice wall. Often, huge blocks of ice get detached from the main ice wall (Naithani et al., 2001 and Vohra, 1981). The wall and the detached ice blocks are clearly identifiable in satellite images. To measure the retreat of the glacier, change in the position of the terminus has to be measured. However, the exact location of the terminus is difficult to identify in medium resolution satellite images such as with Landsat TM (Paul, 2001). In this study, the first pixel showing the ice wall was identified.

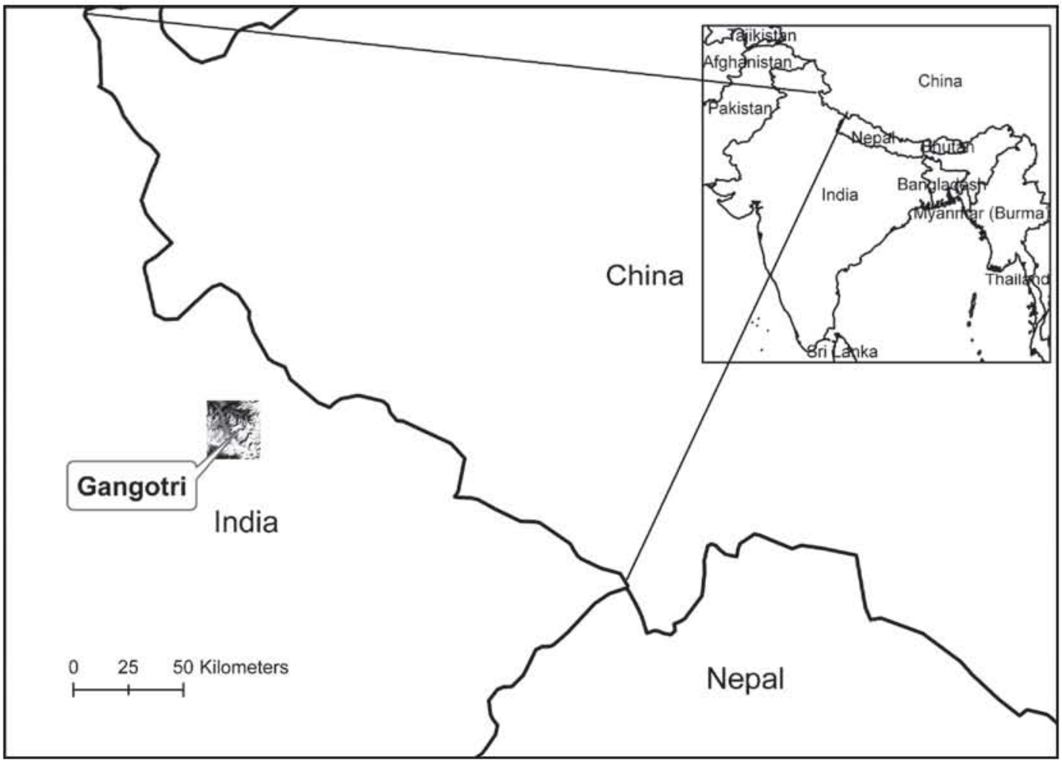

Figure 1: Map showing the location of the Gangotri glacier in the Himalayas

For this purpose, various image ratios and band combinations were used. Band combination of 5, 1 and 3 in Landsat TM and ETM+ seemed very useful in identifying the ice wall and water. Normalized difference water index (NDWI) was calculated for each image using the following equation:

$$NDWI = \frac{Green - NIR}{Green + NIR}$$

Equation 1

where Green is a green band such as TM band 2, and NIR is a near infrared band such as TM band 4. This index maximizes the reflectance of water by using green wavelengths and minimizes the low reflectance of NIR by water features. It takes advantage of the high reflectance of NIR by soil features. As a result, water features have positive values, while soil usually has zero or negative values (McFeeters, 1996). The resulting image clearly shows positive values for pixels with water in the terminus. A band ratio of NIR and mid-wavelength infrared (MWIR) bands (ex. TM 4 / TM 5) was calculated to improve the accuracy of identification of the location of the terminus. This ratio is a useful tool to map the ice (Paul, 2001). A combination of the NDWI image and the band ratio images along with the Band combination of 5, 1 and 3 (for TM and +ETM images) was used in visual identification of the pixel showing the beginning of the ice wall. In the case of Landsat MSS, as these images do not have an MWIR band, only NDWI and false color composite were used to identify the location. Once the location of the wall has been identified in each year, distances between the locations of the walls in different years were measured as straight-line distance. Since this study is not measuring the location of the snout, the rate of retreat identified may not be comparable to the previous studies on the Gangotri glacier.

An analysis of the trends of monthly average temperature and precipitation at the nearest weather station for the decades of 1970s, 1990s and 2000s was conducted to study the possible relationship between weather patterns and glacier retreat. Since there were no weather stations near the Gangotri glacier, this study used the data from the closest weather station in Dehradun (about 300 km). Although the data from Dehradun station do not provide information on specific climate variations in Gangotri, these data will provide an overall picture of variations in climatic conditions in the region. The weather data for Dehradun station were downloaded from NOAA Satellite and Information Service Website (http://lwf.ncdc.noaa.gov/oa/ncdc.html).

3. Results and Discussion

The terminus of the Gangotri glacier has an ice wall apparent in the satellite image. The terminus has undergone marked changes in shape and position over the years (Naithani et al., 2001). Figure 2 shows the Gangotri glacier and the amount of retreat in the location of the ice wall of the glacier. The main glacial stream emerges out from the ice cave in the terminus. The ice cave is wider at its opening and becomes narrow towards the interior. The results of Landsat image interpretations showed there was a 700m straight-line retreat in the ice wall's position in February 2009 compared to its position in November 1976. Thus, the average annual retreat of the ice wall in the longitudinal direction is about 22m during the study period. The amount of retreat seems to be uneven over the last four decades. Between 1976 and 1979, there was a 32m annual retreat in the position of the ice wall. Between 1979 and 1990, there was a 25m retreat annually. Between 1990 and 1999, however, there was about a 37m annual retreat in the ice wall's position. There were longitudinal shifts in the position of the ice cave during these years. For example, between 1999 and 2006, although there was only a 30m latitudinal retreat, there was a 100m southwestward shift in the position of the ice cave. Similarly, between 2006 and 2009, there was a 27m latitudinal retreat, but there was 76m southeastward shift in glacier's wall location in the terminus. Previous studies (Naithani et al., 2001) on Gangotri glacier have identified the change in location of the ice cave in the terminus. Since the width of the ice wall ranges from 35 to 40m, and the resolution of Landsat TM and ETM+ images is 30m, the accuracy of this result was within 30m (or one pixel). In the case of Landsat MSS (for 1976 and 1979), the positional accuracy is within 57m. Therefore, the estimation of the position of the wall between 1976 and 1979 has very low accuracy in this study. An inset picture in Figure 2 shows the position of the ice wall in different years. It is also obvious from this inset picture that it is difficult to locate the position of the ice wall very accurately using medium resolution images. To validate the result of this study, data from the study were compared to data from the previous estimation of the Gangotri glacier recession using filed measurements. Vohra (1981) observed from 1975 to 1990 about 29.8m annual retreat. The results of this study found that between 1976 and 1990, the rate of annual retreat was about 26m.

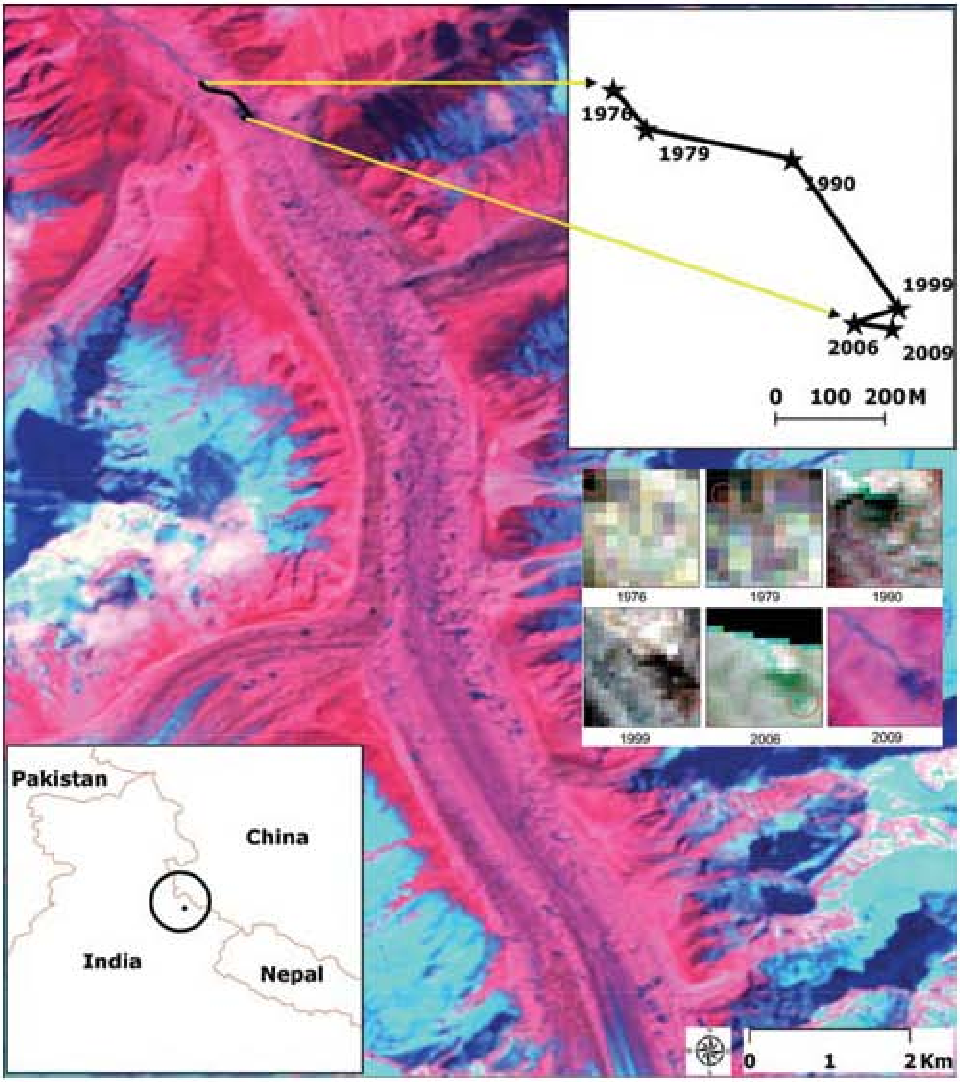

Figure 2: Recession of the Gangotri glacier from 1976 to 2009

This is partly attributed to the large annual fluctuations in the rates of snowfall and precipitation (Naithani et al., 2001). Since the Himalayan glaciers are summer accumulation types, temperature and precipitation patterns during summers could influence the glacier's recession. Figure 3 clearly indicates that within the region the average temperature values during monsoon season and winter period were lower in the 1970s compared to the values for the 1990s and 2000s. However, the average monthly precipitation was generally lower in the 1970s compared to the 1990s and 2000s (Figure 4). Although precipitation values were higher in the 1970s, the June to December temperature values were lower compared to temperatures during the same period in the1990s. The average temperature and precipitation values were very similar in the 1990s and 2000s. These regional variations in the climatic factors could have influenced the variation in the rate of retreat of the Gangotri glacier.

4. Conclusions

Glacier retreats in the Himalayas are one of the major concerns for environmentalists, livelihood advocates, and scientists alike. In unfriendly terrain, as in the Himalayas, monitoring glacier retreats is always challenging. In this situation, remote sensing techniques help in monitoring glacier conditions. The objective of this study was to measure the planimetric change in the Gangotri glacier in the Himalayas using Landsat satellite images. Medium resolution satellite images, such as Landsat, are useful in observing the glacier retreat.

However, very high resolution images are required to identify the exact position of the glacier terminus in remote Himalayan glaciers. This study found an annual average retreat of 22m between 1976 and 2009 in the Gangotri glacier. The study also found that in the more recent years, there was more longitudinal shift in the cave's location than the amount of latitudinal retreat.

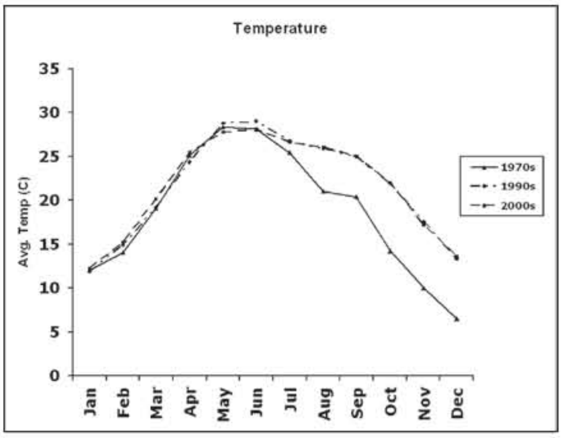

Figure 3: Fluctuations in average temperatures in Dehradun weather station near the Gangotri glacier (Data Source: NOAA Satellite and Information Service)

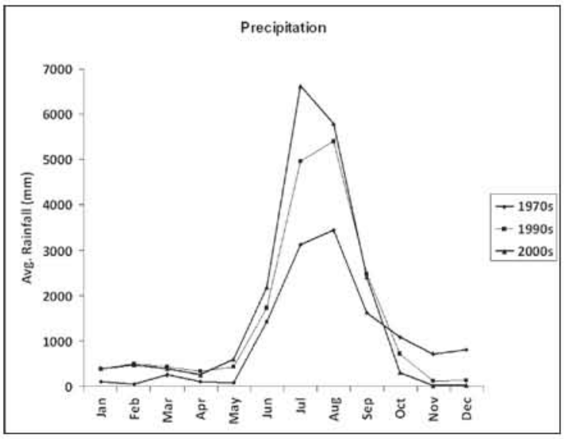

Figure 4: Fluctuations in average precipitation in Dehradun weather station near the Gangotri glacier (Data Source: NOAA Satellite and Information Service)

The results of this study support the observations of earlier studies (Vohra, 1981, Naithani et al., 2001 and Kargel, 2004) of a retreat in Gangotri glacier. Fluctuations in the temperature and precipitation during monsoon season and during the winter could have influenced the recession in the Gangotri glacier. However, an in-depth study is required to link the fluctuations in climatic conditions and the amount of retreat in the Himalayan glaciers. For future study on the Gnagotri glacier retreat or any other glacier in the Himalayas, use of high resolution satellite imagery along with ground observation is necessary. Calibration of various satellite images to improve the accuracy of classification of ice, snow and debris will help to accurately measure the retreat of the Himalayan glaciers.

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