

# CLIMATE CHANGE SIGNALS DETECTED THROUGH MASS BALANCE MEASUREMENTS ON BENCHMARK GLACIER, HIMACHAL PRADESH, INDIA

**Rajesh KUMAR**

Remote Sensing Division, BISR, Statue Circle, Jaipur-302005, India  
*rajeshbhu@yahoo.com*

**Syed I. HASNAIN**

HIGH ICE-India, New Delhi, India

**Patrick WAGNON, Yves ARNAUD, Pierre CHEVALLIER**

UR Great Ice (R032), IRD, Montpellier and Grenoble, France

**Anurag LINDA, Parmanad SHARMA**

PhD Students, Jawaharlal Nehru University, New Delhi, India

## ABSTRACT

In the Indian subcontinent (South Asia), the cryosphere (glaciers and snow covers) provides up to 80% of the low land dry season flows of the Indus, Ganges and Brahmaputra river system through their vast irrigation network. Deglaciation is considered to be a world-wide problem; there is a particular concern at alarming rate of retreat of Himalayan glaciers. The cryosphere retreat is likely to lead a temporary increase followed by reduction in river flows but the quantity, timing and consequences are unknown. It has been estimated in the IPCC report of 2001 that the global temperature rise at the rate of +0.03 °C/year will have a great impact on the sensitive ice mass of the glaciers. The mass balance study started by the initiative of former ICSI, presently known as Commission on Cryospheric Sciences, in 2002 at Chhota Shigri (benchmark) Glacier (32°11' - 32°17' N and 77°30' - 77°32' E), located in the Lahaul and Spiti valley, Himachal Pradesh, India. This glacier is unique as it receives nourishment both by southwest summer monsoon and westerlies. This work is being conducted in collaboration with the Great Ice Research Unit of the *Institut de Recherche pour le Développement*, France and field measurements have been carried out during years 2002-2005.

The study based on the two years of observations shows a negative mass balance of -1.06 and -1.20 m w.e. for the year 2002-03 and 2003-04 respectively. This has increased slightly in hydrological year 2003-04 as compared to hydrological year 2002-03. The glacier is likely to become thinner at lower altitudes, as there is increased negative net mass balance year to year.

The Equilibrium line altitude (ELA) is also shifting upward and stays at an interval of 4800-5100 m, thus reducing the accumulation area. The results clearly indicate the impact of warming in the region.

The work is still continuing and long term mass balance measurements will indicate about the climate signals affecting the cryosphere in the South Asia.

**Keywords:** Himalaya, mass balance, runoff, southwest summer monsoon, Westerlies, ELA

## INTRODUCTION

The Hindu-Kush-Himalaya represents a 'critical region' in terms of glacier melt water contribution to irrigation network for millions of South Asians. The glacier response with the climate is closely associated and has been a central issue in glaciological studies (e.g., Kuhn, 1981; Oerlemans, 1994). Glaciers are so sensitive to climate variations that it can be used as an indicator of climate change, but like a thermometer, the relation between climate change and glacier response needs to be calibrated. This is not only helpful in understanding present climate but is also critical to responding past climate change or predicting future glacier responses. In tropics, glacier-atmosphere interactions are complex because accumulation and ablation are synchronous and ablation is permanent throughout the year (e.g., Hastenrath and Ames, 1995; Kaser, 2001). Changes in glacier length, areal extent or mass balance can also be used as climate indicators in a region where climatic data series (temperature, precipitation) are rare and the climate change signal is not clear (Yadav et al., 2004; Roy and Balling, 2005). Combined glacier mass and energy balance studies on low-latitude glaciers provide valuable knowledge on the tropical and global climate (Wagnon et al., 2001; Francou et al., 2003). As global climate changes, there is an accordant trend towards global recession and wasting of glaciers. Several analyses show that it is not

only increased temperature and/or decreased precipitation that are responsible for these retreats, but also changes in air humidity (Kaser *et al.*, 2002).

In addition, for the people living in the Himalayan valleys, runoff generated by the melting of these glaciers is an important source of water in the perennial rivers originating from Himalaya (WWF, 2005). The problems of water stress are already prevalent in the region due to increasing demands of domestic, agriculture, industry and a growing population. Any reduction in the availability of freshwater could have serious consequences for the economy, the environment and the daily lives of many millions of people within the affected basins and beyond.

Still the importance of looking to the climate change effects on glaciers and its impacts on subsequent freshwater supply has not been addressed in an integrated manner. Lack of which has been reflected in the idleness of the policy makers to look to the matter while dealing with long term sectoral development planning of the region especially in the Hydropower and Agricultural sectors.

Glacier mass balance is a link between climate and glacier dynamics. Mass loss affects the local hydrology because mass is lost generally through melt-water runoff. Thus the prediction of mass balance change is also a prediction of their hydrological effect, which is important for regional water supplies. In the present study an attempt has been made to check climate signals by monitoring mass changes. The sensitivity of the equilibrium line altitude (ELA) is also discussed, which is closely associated with the change in temperature and the precipitation in the glacier valley.

## STUDY AREA

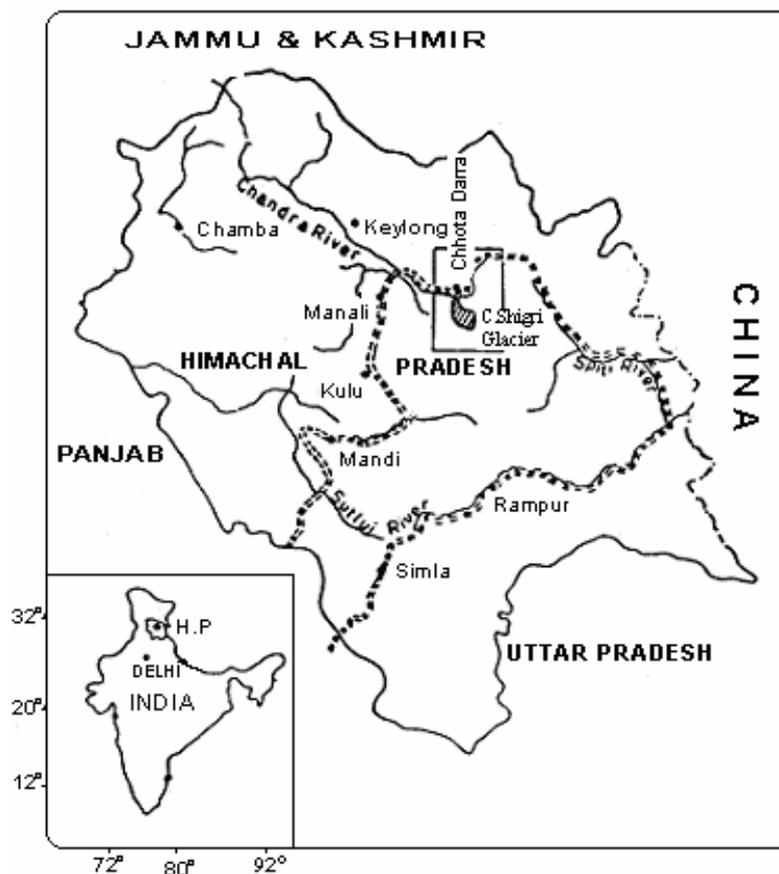


Fig. 1: Location map of the Chhota Shigri (benchmark) glacier, Himachal Pradesh, India.

Chhota Shigri glacier is the study area, which lies in the Himachal Pradesh, India and was selected as benchmark glacier in the HKH region by the International Commission of Snow and Ice (now this is Commission of Cryospheric Science) in 2002. Chhota Shigri glacier lies on the Chandra-Bhaga river basin on the northern ridge of Pir Panjal range in the Lahaul-Spiti valley of Himachal Pradesh. It is included in the upper basin of the Chandra River, which latter joins Bhaga River and together contribute

to the Chenab River, one of the components of the Indus basin, is located about 3 km (glacier terminus) south of Chhota Darra across the left bank of Chandra River (the main river of this region), is trending about N-S to NNE to SSW (Figure 1). This glacier extends between 32°11' - 32°17' N and 77°30' - 77°32' E and occupies an elevation of 4000 to 5660 m a.s.l. It extends for about 9 km in length and the width is varying from 0.3 to 1.5 km (Figure 2). The highest peak (6000 m a.s.l.) is at the eastern side from which four small glaciers feed the main accumulation zone (Nijampurkar *et al.*, 1993).

Alternatively influenced by the Asian Monsoon during the summer, and submitted to the westerlies in the winter, the glacier offers a complex accumulation/ablation regime. The glacier falls in the monsoon-arid transition zone; therefore this glacier is considered to be a potential indicator of the northern limits of the intensity of the monsoon (Krenek and Bhawan, 1945). This glacier is unique in its characteristics as it receives nourishments both by southwest monsoon and westerlies. Melt-water from the glacier surface penetrates the ice body and forms sub glacial channels, and a few surface melt water channels are also observed along the middle of the glacier during the summer months. The total drainage area of the Chhota Shigri basin is about 45 km<sup>2</sup>, with a glacierised area of approx 10 km<sup>2</sup> and the glacier occupies about 22 % of the drainage area (Dobhal *et al.*, 1995). It is a valley glacier and the shape is complex; including two main flows in the central part and several small suspended sub-glaciers in the accumulation zone. The lower portion of the glacier is covered by debris. The thickness of the glacier ice varies from 15 to 130 metres from the snout to the accumulation zone according to the gravity survey (Kumar and Dobhal, 1997).

## **GEOLOGY OF THE AREA**

Chhota Shigri glacier lies within the central Crystallines of the Pir Panjal range of the Himachal Himalaya. This crystalline axis is comprised mostly of meso- to ketazonal metamorphites, migmatites and gneisses. In few places, granitic rocks of different composition and younger age indicate rejuvenation but 3 km upstream of Chhota Dara, in the upper Chandra valley; older Palaeozoic granitic rocks are exposed. The Haimanta formation overlies these with a tectonic break, where black slates, phyllites and fine-grained biotite-schists are exposed. The slates and phyllites show a well developed thrust tectonic contact, which forms the crest of the northern ridge. Box type folds with decollement are quite prominent in the Haimanta Formation. The Haimantas, which rest directly on basement rocks, are highly metamorphosed metasediments and show intense folding and shearing. The brown biotite, with a fine-grained texture, shows intense heating effect, which indicates periodic re-heating of the granite rocks below. The various types of granite and gneiss rocks present in the basement also indicate this. Schistose gneiss and augen gneiss has developed in the granite without any distinct margins. Chhota Shigri glacier rests on the granitic basement rocks. On both sides the ridge tops are at an altitude of 6300 m and the bottom of the Chandra Valley lies at 3300 m and the overall relief is 3000 m.

## **CLIMATE**

The climatic records of the region are not available but the nearest weather station at Keylong records a maximum temperature of not exceeding 24 °C. The region is mainly characterised by the cold winter extending from October to April. The short term meteorological observations (July to September) on the glacier during 1987-1989 showed a temperature ranging between 10.5 °C to -5.2 °C at an elevation of 4600 m while 16 °C to 4 °C near snout (Dobhal *et al.*, 1995). The main valley (3000-7000 m deep), in which the glacier is situated, is dry. The annual precipitation on the glacier is 150-200 cm of snow (~600 kg m<sup>-2</sup> year<sup>-1</sup>). The average environmental lapse rate on Chhota Shigri glacier remained pseudo-adiabatic on most days during the summer and varied from 0.38 °C to 0.67 °C/100 m (Bhutyani and Sharma, 1989).

## **METHODOLOGY**

This mass balance study was started by the initiative of former International Commission of Snow and Ice (ICSI), presently known as Commission on Cryospheric Sciences, in 2002 (September-October) at Chhota Shigri glacier. Since then the work is being continued in collaboration with Institut de Recherche

pour le Développement (IRD), France and Society for Himalayan Glaciology, Hydrology, Ice, Climate and Environment (HIGHICE –India).

The glacier mass balance study needs to be observed every year during the end of hydrological year, which is from October 1<sup>st</sup> to September 30<sup>th</sup> next year. In this respect the glacier has been revisited annually in September for the measurements of old stakes and installation of new stakes. During the field expedition from September 18 to October 10, 2003, the stake's position of 2002 was re-measured with the help of differential GPS and melting was observed through the differential exposure of stakes measurements. The new stakes were installed on the glacier and the number has been increased to 22 from 14 in order to increase the stake density for better accuracy of the mass balance. Accumulation pits were dug to know the yearly accumulation. The hydrological measurements were also performed at the down stream of snout.

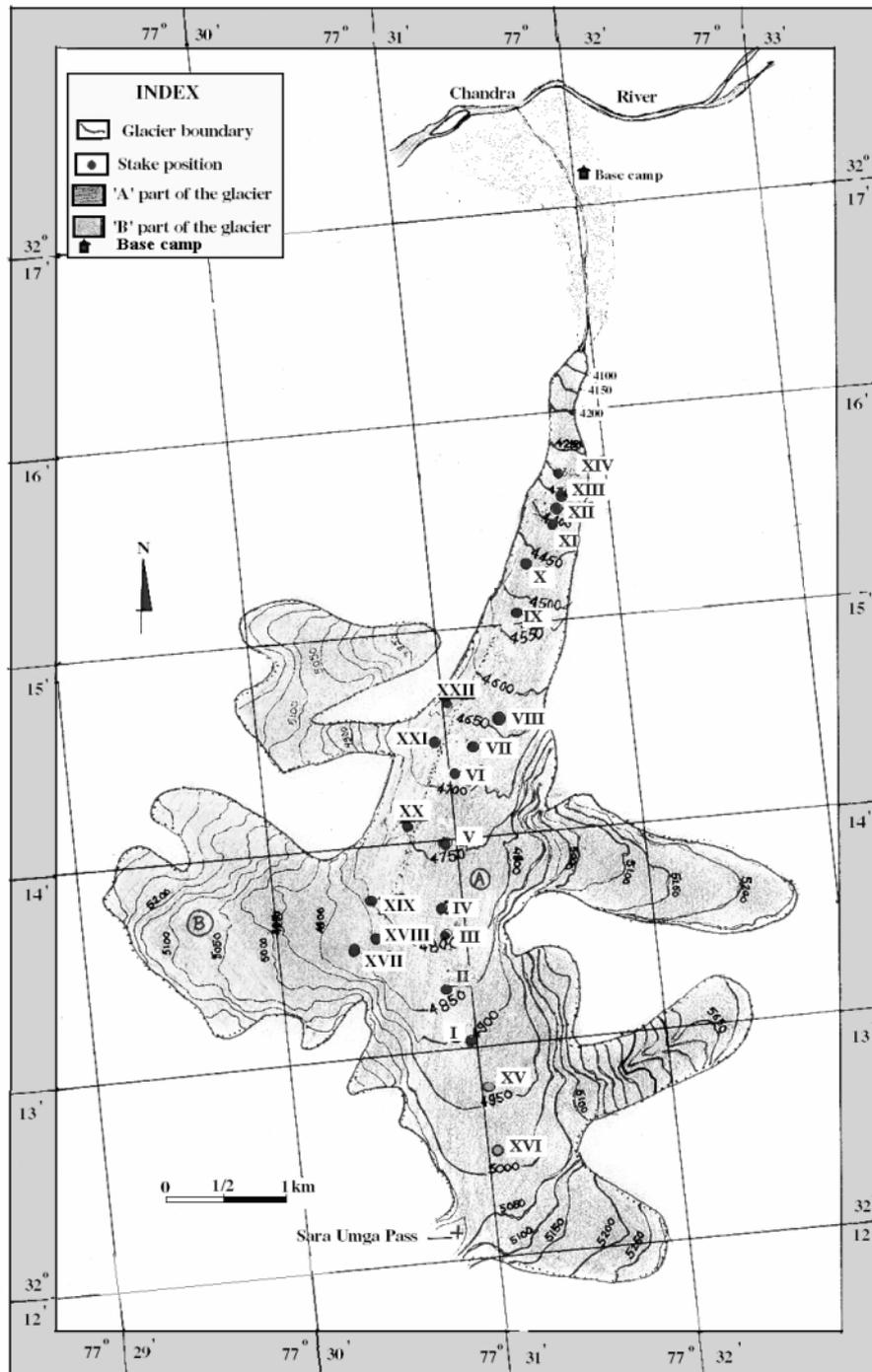


Fig. 2: Stakes installed on the Chhota Shigri glacier during September-October, 2003.

A field campaign during September 14 to 28, 2004 was organised to revisit the glacier for the measurement of 2003 stakes and to put the new stakes on the glacier. The stakes density has been increased further to 27 as compared to 22 in year 2003. Three accumulation pits were dug to know the yearly accumulation at nearly the same place where the last year's observations were performed. The stakes installed in first week of October 2003 is presented on the topographic map of the Chhota Shigri glacier (Figure 2). This clearly shows the distribution of stakes in 2003 on the Chhota Shigri glacier.

### Glacier flow velocity

Differential Geopositioning System (DGPS) was used to measure the coordinates of stakes installed in 2003 and again the same stake in 2004. Displacement of the stakes gave the velocity of the glacier on that altitude. The results so obtained are represented graphically against the altitude (Figure 3). It is observed that the middle ablation zone of the glacier has higher velocity about 40 m/year while the lower ablation and ELA zone shows less velocity of about 25 m/year. The glacier flow velocity reported earlier was 8.1 m/year in the ablation zone to 13.81 m/year at the ELA (Dobhal, 1992). This one year result shows that the glacier flow has increased in last one decade.

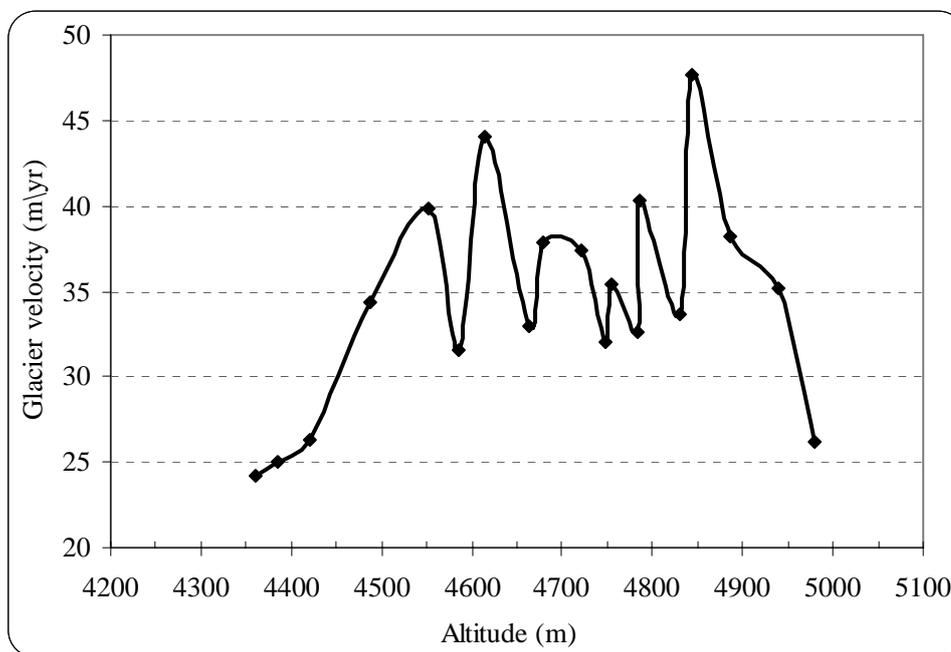


Fig. 3: Annual glacier velocity in the different altitude zone of Chhota Shigri glacier in 2003-04.

### Accumulation measurements

In the accumulation area of Chhota Shigri glacier, three snow/finn pits were dug to obtain information on yearly accumulation of the snow. The only recognisable changes in the stratigraphy were slight differences in the size of the finn grains and few thin ice layers. The ice layers were clear at some places while dirty at the other places.

The vertical density measurements are performed to calculate accurately the water equivalent of snow accumulation in one year. Density profiles of all the three pits are presented for years 2003 and 2004 in Figure 4 and 5 respectively. Very little changes in the density profile have been observed for the first two pits at the elevation of 5200 m and 5405 m in the year 2003. The density first increases and then decreases with depth. The third pit (year 2003) at an elevation of 5500 m shows a large variation in the density profile increasing with depth and reaching to  $0.86 \text{ g cm}^{-3}$  (glacier ice) at the depth range of 300-338 cm. In the year 2004, the pit at 5180 m shows clean ice with bubbles in the depth range of 25 to 165 m showing a density of  $0.79 \text{ g cm}^{-3}$  and thereafter decreased to  $0.58 \text{ g cm}^{-3}$  at the depth of 220 m. The two upper elevation pits (5400 m and 5500 m) are showing the same trend and density reaches up to  $0.8 \text{ g cm}^{-3}$  at several depths as the ice layers were observed.

## Glacier mass balance

Crucial to the survival of a glacier is its mass balance, the difference between glacier ice accumulation and ablation (melting and sublimation). Climate change may cause variations in both temperature and snowfall, causing changes in mass balance. A glacier with a sustained negative balance is out of equilibrium and will retreat. In the ablation area, local net ablation is evaluated using a network of ablation stakes (6 to 10 m-bamboo stakes stuck into the glacier at various altitudes using a steam-drilling device). The emerged part of the stakes is measured every year at the beginning of October together with ice/snow density and the emergence difference gives the annual ablation at that point.

At every point on a glacier, there is a specific net mass balance. In general, this is positive at higher altitudes, where accumulation is more and negative at lower altitudes where the ablation is greater than the accumulation. The net balance of a particular glacier may vary sharply from one year to another. In order to obtain an accurate picture of glacier changes, mass balance programmes, therefore need to be continued for many years. The shape, or geometry, of a glacier may have a significant effect on its mass balance.

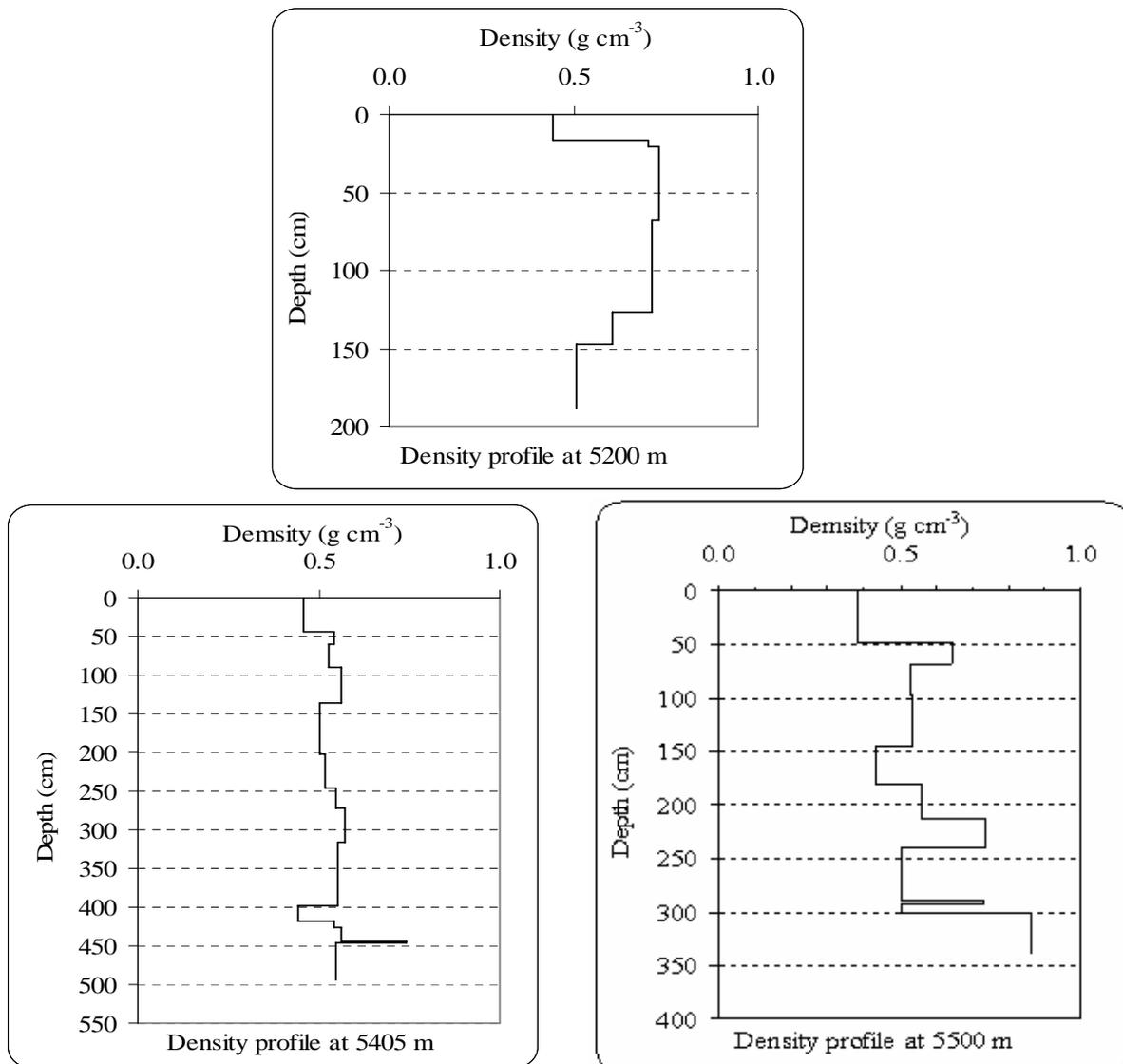


Fig. 4: Vertical density profile of accumulation pits at different elevations in 2003.

The glacier's annual net mass balance is calculated from the measurements of the winter and summer balances but in our case we took only the annual measurements in last week of September every year and calculated the annual balance. The surface area of a glacier is divided into altitudinal zones based on the contours of 50/100 m and stakes and pits features are the representative of the zone in which they are

falling. The average accumulation and ablation is calculated from pits observation and the differential exposure of the stakes respectively on yearly basis. The surface area of each altitudinal zone used in mass balance calculations is based on Survey of India topographic maps.

**Specific net annual mass balance**

Based on the two years of the stake measurements (2002-03 and 2003-04) the specific net mass balance is calculated at every point of stake's and presented in graphical form (Figure 6 and 7) against the representative elevations of the stakes. The glacier melt increases from higher altitude towards lower altitude from 4917 m to 4370 m and suddenly the melting reduces for two stakes in the lower ablation zone. This sudden decrease of melting may be due to the reduction in sunshine hours at this region because of narrowing of the valley, which is observed during the field visit. This reduced ablation may also be due to heavily debris covered zone just above the snout region.

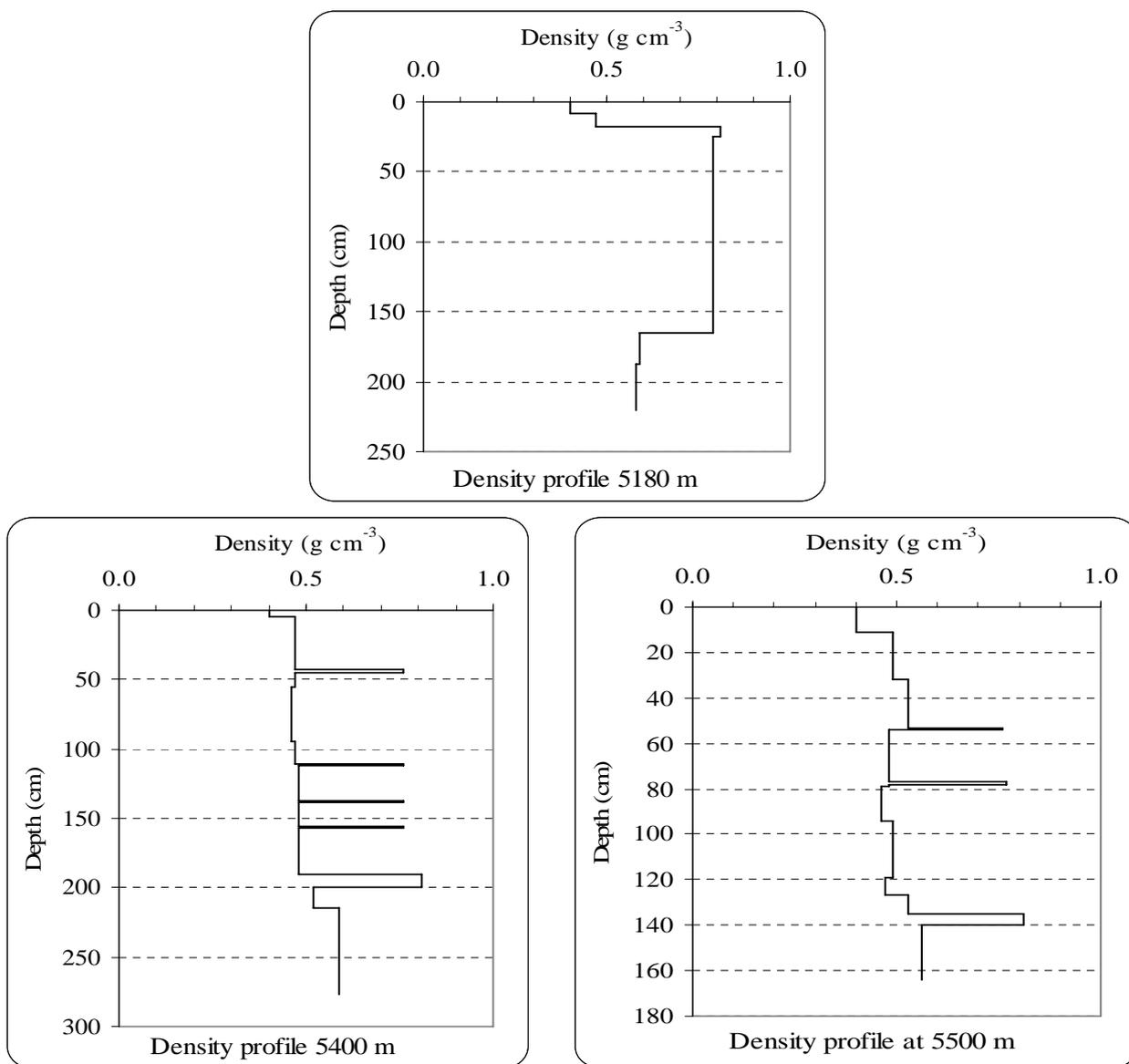


Fig. 5: Vertical density profile of accumulation pits at different elevations in 2004.

**Net mass balance**

The various positions of the snout line monitored during 1987-89 (campaign of Department of Science and Technology, New Delhi) are an indication of the annual climatic variation on the glacier and have been accompanied by three main episodes of advance and retreat. Fluctuations of the equilibrium line, observed during the same period, support the above observations. The snout line of the glacier continued to recede at a rate of  $18.7 \text{ m year}^{-1}$  during 1986-88. This retreat was accompanied by a negative mass balance observed during 1987-88 (Nijampurkar and Rao, 1992).

Our study based on the two years observations (2002-03 and 2003-2004) shows a negative specific mass balance of  $-1.06 \text{ m w.e.}$  and  $-1.20 \text{ m w.e.}$  for 2002-03 and 2003-04 respectively. The increased negative mass balance in 2003-04 reflects more thinning of glacier at lower altitude.

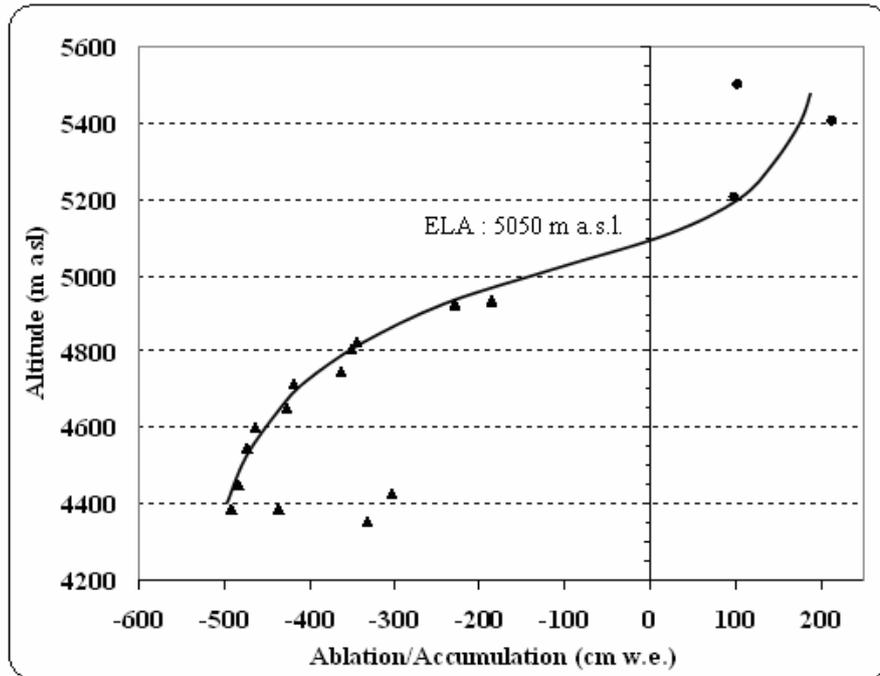


Fig. 6: Specific net annual mass-balance (2002-03) near measurement points averaged against the elevation on Chhota Shigri glacier.

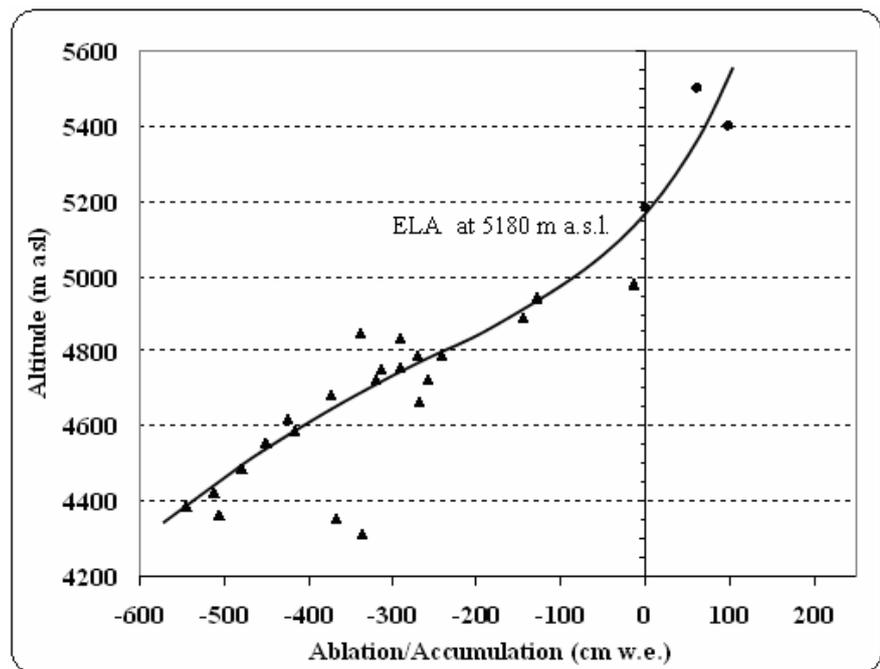


Fig. 7: Specific net annual mass-balance (2003-04) near measurement points averaged against the elevation on Chhota Shigri glacier.

## **Equilibrium line altitude (ELA)**

At the end of the summer, the equilibrium line marks the position at which summer ablation just equals the accumulation of the preceding winter. The equilibrium line altitude (ELA) is the most suitable parameter for interpreting glacier responses to climate variations. The sensitivity of the ELA to climate variations depends on the gradients of the mass balance terms at the respective altitudes. In order to study the sensitivity of the equilibrium lines under the different conditions their mean positions in the respective vertical profiles of specific mass balance has to be determined. Frequently, there is a clear relationship between the equilibrium line altitude (ELA) and the net mass balance of the glacier. The ELA varies from year to year and shows a fluctuating nature.

The ELA during years 1987, 1988, and 1989 were at an altitude of 4650, 4750, and 4840 m a.s.l. respectively (Dobhal *et al.*, 1995). The ELA calculated from the vertical profiles of specific mass balance on Chhota Shigri glacier for years 2003 and 2004 has to be determined and are respectively 5050 and 5180 m a.s.l. (Figure 6 and 7). These comparisons very clearly indicate that the ELA is shifting upward which is not a good sign for the glacier. This upward shift of ELA exposes more ice to the ablation zone for melting. The accumulation area ratio (AAR) has also decreased from 0.40 (in 2003) to 0.31 (in 2004). The earlier study by Dobhal *et al.* (1995) has reported the AAR as 0.73, 0.59 and 0.39 during years 1987, 1988 and 1989 respectively. This decrease in AAR values gave the glacier a threat for the more melting which is also evident from the calculated net mass balance of the glacier for year 2002-03 and 2003-04.

## **CONCLUSIONS**

The climate change impacts are clearly visible on the benchmark glacier (Chhota Shigri) as evident through the increase in the net loss of mass year by year. The glacier is likely to become thinner at lower altitudes, as there is increased negative net mass balance. The ELA variation in 17 years, which was at 4650 m in year 1987, has moved to 5180 in 2004 gives an average rate of upward shifting by 31 m/year. The decrease in AAR value in two years gave the glacier a further threat for the more melting as the accumulation area has reduced and the ablation area has increased in these years. This result is also supported by decrease in net mass balance of the glacier. All together the sharply changing behaviour of ELA shifting upward and reduction in AAR value may be due to the effect of climate change induced warming and the variation in precipitation in the region.

## **ACKNOWLEDGEMENTS**

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