EFFECT OF GLOBAL WARMING ON THE HIMALAYAN CRYOSPHERE

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ABSTRACT *In the Himalayas, a large area is covered by glaciers and seasonal snow and changes in its extent can influence availability of water in the Himalayan Rivers. This paper discusses changes in glacial extent, glacial mass balance and seasonal snow cover. Glacial retreat was estimated for 466 glaciers in Chenab, Parbati and Baspa basins since 1962. The investigation has shown an overall reduction in glacier area from 2077 km^2 to 1628 km^2 since 1962, an overall deglaciation of 21%. Glacier mass balance was estimated using accumulation area ratio method and investigations suggest a loss of 0.2347 km^2 of glacial ice between 2000 and 2002. Seasonal snow cover was monitored in the Baspa river basin using NDSI technique. In early part of winter, i.e. from October to December end, large amount of snow retreat was observed. In addition, average stream runoff of the Baspa basin for the month of December has increased by 75%. This combination of glacial retreat, negative mass balance, early melting of seasonal snow cover and winter time increase in stream runoff suggest an influence of climate change on the Himalayan cryosphere.*

Key words Cryosphere; deglaciation; stream runoff; snow cover; glacier area.

INTRODUCTION

Over the past three millions of years, the earth's surface has repeatedly experienced large periods of glaciations separated by short warm interglacial periods. During the peak of glaciations, an approximately 47 million km^2 area was covered by glaciers, three times more than the present ice cover of the earth (Price, 1973). Numerous ideas were proposed to explain repeated cycles of glaciations on the earth. One of the possible explanations could be the natural variation in the earth’s orbit around the sun. These orbital cycles (100,000, 41,000 and 22,000 years) can cause 10% variation of incoming solar radiation in various parts of globe (Ruddiman, 2005). These regular changes in the amount of sunlight reaching on the surface of the earth might have produced repeated cycle of glaciations. This can also produce asynchronous behaviors in development of glacial extent in the Northern and Southern Hemispheres. This aspect was extensively studied in tropical Andes and maximum extent of last glaciations was estimated around 34,000 years ago and which retreated by 21,000 years before present (Smith et al., 2005). This cycle of glaciations is different than reported in the Northern Hemisphere, where the peak of the last glaciations in late Wisconsin was estimated approximately about 17,000 to 21,000 years ago (Denton and Hughas, 1981).

Natural variations in the earth’s orbit are well synchronized with atmospheric variations in methane and carbon dioxide, leading to repeated cycle of glaciations. However, this natural cycle might have altered due to greenhouse effect, caused by man-made changes in the earth’s environment. Some of the hypotheses suggest this alteration might have started long before the beginning of industrial revolution

(Ruddiman, 2005). Invention of agriculture about 11,000 years ago might have led to large-scale deforestation and rice cultivation. However, this pace of change might have got accelerated from the beginning of industrial revolution. This has lead to an increase in global temperature by 0.6 ± 0.2°C since 1900 (Lozan et al., 2001). In addition, recent developments in climate modeling suggest that existing greenhouse gases and aerosols in the atmosphere have lead to absorption of 0.85 +/- 0.15 W/m more energy by the earth than emitted into space. This means additional global warming of about 0.6°C without further change in atmospheric composition (Hansen, 2005). This observation was further supported by Fourth Assessment Report published by Intergovernmental Panel on Climate Change in 2007, where warming of 0.2°C per decade is projected for the next two decades, even if the concentration of all greenhouse gases and aerosols is kept constant at year 2000 level. In addition, best estimates of globally average surface air warming for different warming scenarios vary between 1.8° and 4.0°C (IPCC, 2007). This will have profound effect on the Himalayan cryosphere.

GLACIER RETREAT

Climate change can significantly influence glacial retreat. However, each glacier is likely to respond to climate change differently, depending upon its size, area-altitude distribution, orientation and moraine cover. Therefore, monitoring changes in the glacial extent is important, as it will have profound effect on availability of water in the north Indian river system. Identification and mapping of glacier boundary and terminus is one of the important aspects of estimation of retreat. If glaciers are not covered by the debris, then identification of snow, ice and rock on satellite images is possible due to substantial difference in spectral

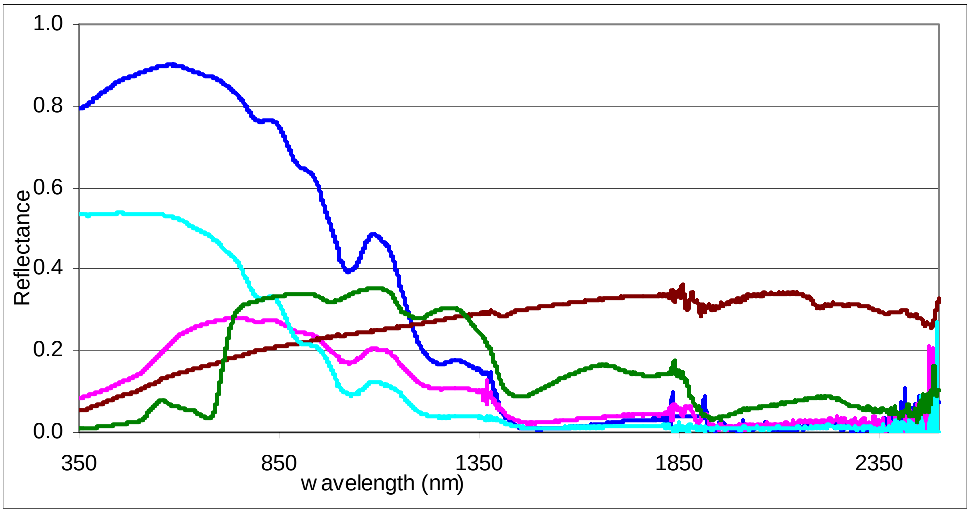

Fig. 1 Spectral reflectance of snow, ice, contaminated snow, vegetation, and soil. These observations were taken using spectral radiometer near Manali, Himachal Pradesh. Please note changes in reflectance as snow changes into ice and as snow and ice is covered by rock debris.

reflectance. Spectral reflectance curves of fresh snow, ice, dirty snow and rock which were obtained near Manali in Himachal Pradesh are shown in Fig. 1.

This indicates substantial difference between snow and rock. In addition, reflectance of ice is also substantially different compared to rock in a region between visible and short wavelength infrared (SWIR). This makes it possible to separate glacial features from other features. In India, glacier inventory is generally carried out using topographic maps of Survey of India and aided by vertical aerial photographs, wherever available (Kaul, 1999). However, this information is stored as a statistical database, rather than in spatial mode and is difficult to use for estimating retreat. Therefore, glacier boundary layer was estimated from topographic maps. Those glaciers were selected for estimating retreat, where geomorphology, as given in topographic maps is comparable with satellite images.

A satellite imagery of LISS-IV sensor showing glacial boundary of 1962 and 2004 is given in Fig.2.

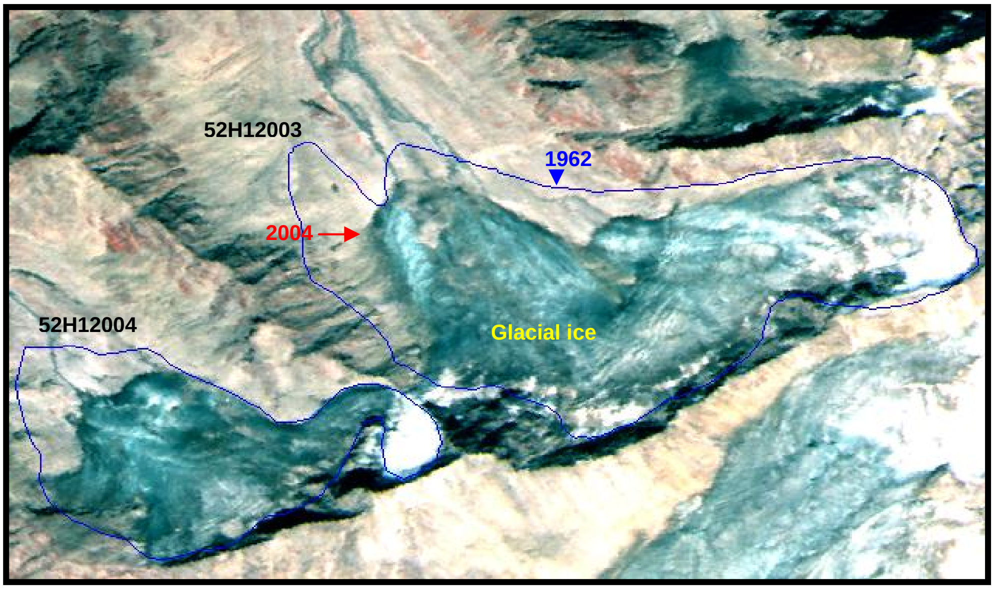

Fig. 2 A satellite imagery of glacier number 52H12003 and 52H12004 of LISS-IV sensor showing glacial boundary of 1962 and 2004. These are small mountain glaciers, showing negligible accumulation area. Maximum altitude of these glaciers is around 5200 m. This is very close to snow line at the end of ablation season and such glaciers are expected to experience terminal retreat.

Identification and mapping of glacial terminus are normally difficult, if glaciers are covered by debris. Numerous geomorphologic features can be utilised to identify terminus. Many times moraine-dammed lakes are formed at downstream of glacial terminus (Fig. 3). These lakes can be easily identified on satellite images (Fig. 4). Some time glacial terminus is characterized by a steep ice wall. Depending upon relative positions of sun and the ice wall, this wall can cost a shadow in downstream (Fig. 5), which can be used as a marker for terminus delineation (Bahuguna et al., 2007).

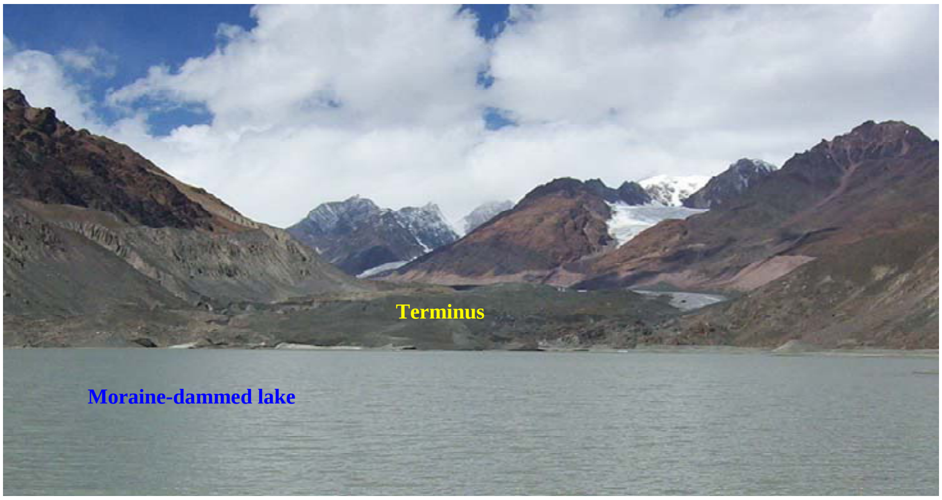

Fig. 3 A field photograph showing moraine-dammed lake near Samudra Tapu glacier, Chenab basin, Himachal Pradesh.

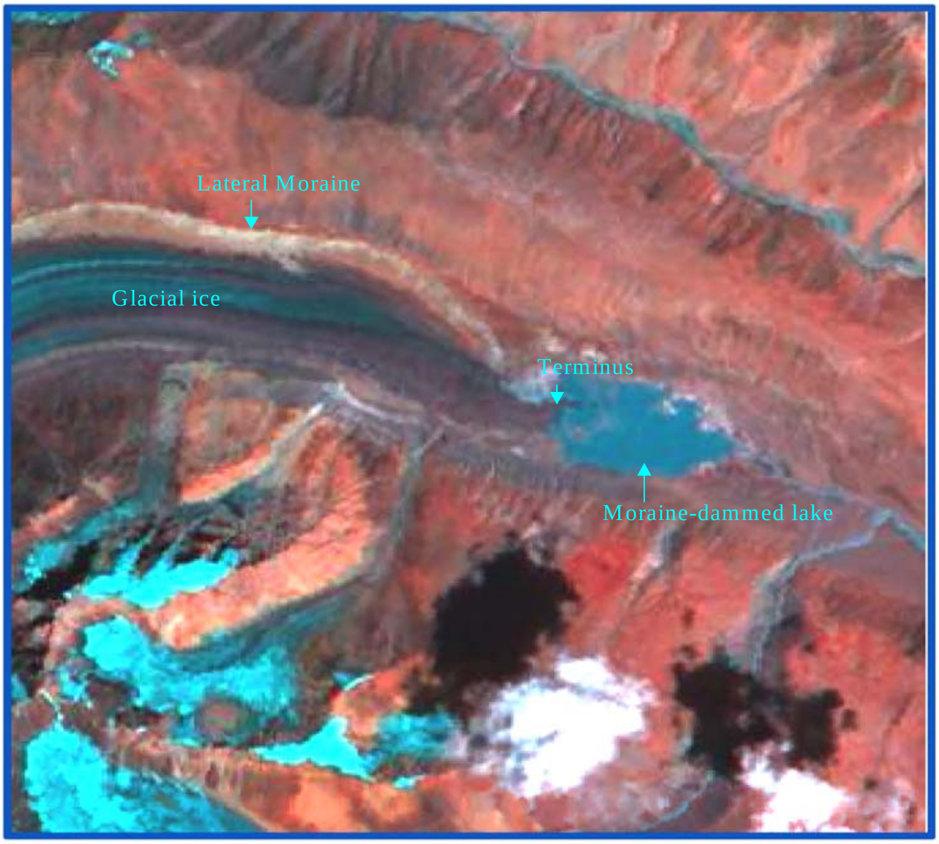

Fig. 4 A satellite imagery showing moraine-dammed lake and terminus of Samudra Tapu glacier, Chenab basin, Himachal Pradesh.

Fig. 5 Satellite imagery of Gangotri glacier characterizing shadow as terminus.

1988

2003

Fig. 6 Field photograph of terminus region of Chhota Shigri glacier, Lahaul and Spiti district of Himachal Pradesh take in 1988 and 2003. In 1988, glacial ice is exposed on the surface and small portion of terminus is covered by debris. By year 2003, entire terminus zone is covered by debris.

In order to estimate glacial retreat, investigations were carried out in Chenab, Parbati and Baspa river basins. Satellite imagery of LISS-III and IV sensor was used. Field investigations at Chhota Shigri glacier were carried out in 1988 and 2003 (Kulkarni et al., 2007), which suggest a retreat of 800 m. Field photographs of glacier terminus region indicate changes in glacial morphology (Fig. 6). In 1988 glacial terminus can be seen clearly whereas during this period entire region is covered by debris, suggesting glacial retreat and reduction in debris carrying capacity of glacier (Kulkarni et al., 2007). If this process continues then this glacier will convert into rock glacier. Field investigation at Patsio glacier has shown concave shape of terminus, indicating retreating glacier (Fig. 7).

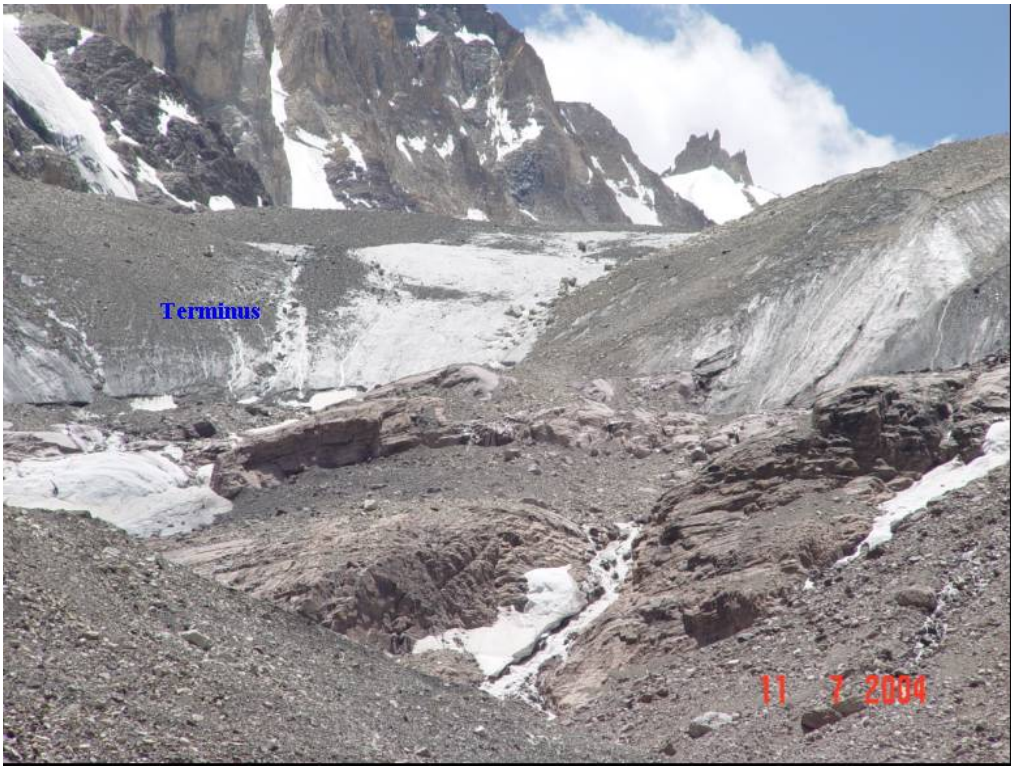

Fig. 7 Field photograph of terminus region of Patsio glacier, Bhaga river basin, Lahaul and Spiti district, Himachal Pradesh. Shape of glacial terminus is concave, suggesting retreating glacier. Glacier ice can be seen clearly and debris cover is relatively less on this glacier.

This was further confirmed as isolated dead ice mounds were observed at downstream of present terminus (Fig. 8), suggesting rapid glacial retreat. Areal extents of 466 glaciers were estimated; the overall area was 2077 km^2 in 1962 and 1628 km^2 in 2001/04, an overall 21% deglaciation. Basin-wise loss in glacier area is given in Table 1.

Table 1 Basin-wise loss in glacier area in Chenab, Parbati and Baspa basins.

Name of basin	Glacier numbers	Glacier Area (km^2)			Volume (km^3)		
		1962	2001/04	Loss %	1962	2001/04	Loss%
Chenab	359	1414	1110	21	157.6	105.03	33.3
Parbati	88	488	379	22	58.5	43.0	26.5
Baspa	19	173	140	19	19.1	14.7	23.0
Total	466	2077	1628	21	235.2	162.73	30.8

Fig. 8 Field photograph of dead ice mound at Patsio glacier. A rock formation between present terminus and dead ice mound can be clearly seen in Fig. 7.

Amount of retreat is varying from glacier to glacier and from basin to basin, depending on parameters such as maximum thickness, mass balance and rate of melting at terminus (Kulkarni et al., 2005). The table suggests that loss in glaciated area depends on areal extent of the glaciers (Table 2). This is possibly because glacier response time is directly proportional to thickness (Johannesson et al., 1989) and thickness is directly proportional to its areal extent (Chaohai and Sharma, 1988). Response time is known as the amount of time taken by glacier to adjust to a change in its mass balance. If maximum thickness of glaciers varies between 150 and 300 m then the response time for temperate glaciers will be between 15 to 60 years (Paterson, 1998). In the Himalayas, if glaciers are not heavily covered by debris, areal extent of glaciers is less than 1 km^2 and rate of meting around snout is around 6 m a^{-1} and then response time can be estimated between 4 and 11 years. Therefore, if other parameters are constant then small glaciers are expected to adjust to climate change faster. This phenomenon is now being observed in the Himalayan region, as glaciers smaller than 1 km^2 have deglaciated by almost 38 % between 1962 and 2001/04 (Table 2).

Table 2 Changes in area extent of glaciers in Chenab basin.

Glacier area (km^2)	Number of glaciers in 1962	Glacier area (km^2)		Change in %
		1962	2001/04	
< 1	127	68	42	38
1-5	159	382	269	29
5-10	48	329	240	27
> 10	25	635	559	12
Total	359	1414	1110	21

On the other hand, larger glaciers have shown only 12% loss in area. Even though, total glacial extent is reduced, numbers of glaciers have increased. Number of glaciers as a function of area for Chenab basin is plotted in Fig. 9. Mean of glacial extent was found to reduce from 1.4 to 0.32 km^2 between 1962 and 2001. In addition, number of glaciers with higher areal extent have reduced and with lower areal extent have increased between 1962 and 2001. This glacial fragmentation can be clearly seen on satellite images (Fig. 10).

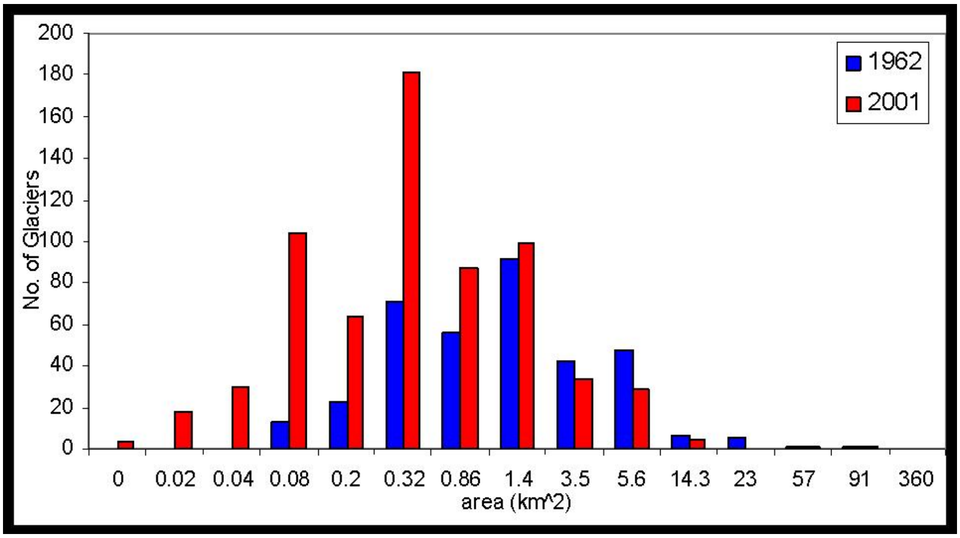

Fig 9 Number of glaciers as a function of area for Chenab basin. Areal extent is increasing by power of 2.

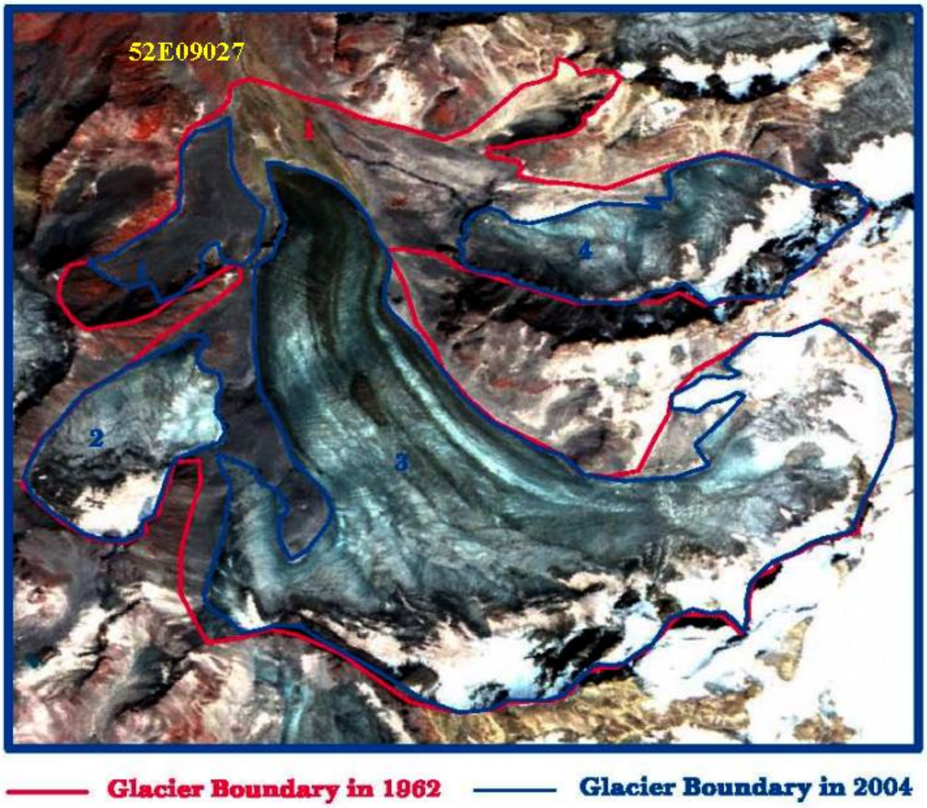

Fig. 10 Resourcesat imagery of LISS-IV sensor dated Sept. 12, 2004 of glacier number 52E09027. This glacier splitted into 4 glaciers between 1962 and 2004. Areal extent is reduced from 7.0 to 5.3 km^2.

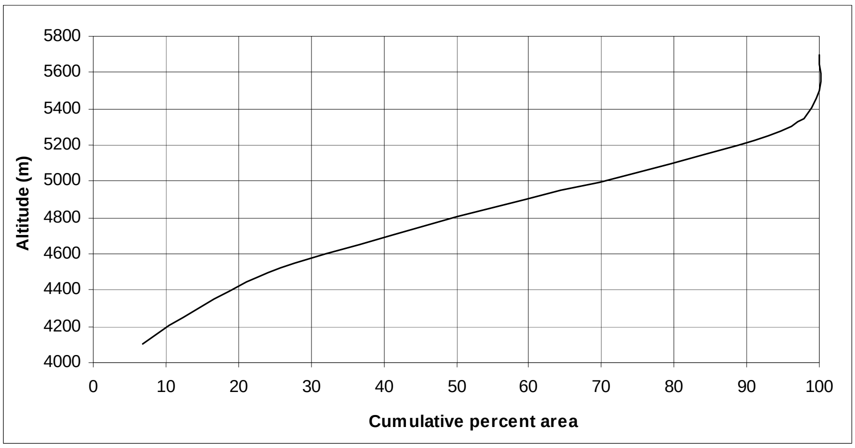

Fig. 11 Area altitude distribution of Parbati glacier. Distribution of glacier in percent below various altitude zones. For example below 4800 m altitude 50 percent of glacier is located.

Another factor, which can influence glacier retreat, is area-altitude distribution, as snow and ice ablation is influenced by altitude. In the Himalayas, snow line at the end of ablation season is approximately 5200 m. If large glacier area is below this altitude, then glacier will experience negative mass balance influencing retreat. For example, Parbati glacier has almost 96% area below 5200 altitude (Fig. 11), causing negative mass balance. This is one of the fastest retreating glaciers in the Himalayan region (Kulkarni et al., 2005).

GLACIER MASS BALANCE

Mass balance of a glacier is usually referred as a total loss or gain in glacier mass at the end of hydrological year (Paterson, 1998). This is estimated by measuring total accumulation of seasonal snow and ablation of snow and ice and can be measured using various methods (Kulkarni et al., 2004). In direct measurement, net balance is measured at representative points on glacier. In photogrammetric method, contour maps are prepared at the interval of few years. Two maps can be compared to determine change in glacier volume. In hydrological method, net balance can be determined for whole basin, by measuring perception, runoff and evaporation. This method needs extensive field investigations and due to rugged terrain of the Himalayas, it can provide mass balance of only few glaciers. In order to obtain mass balance of large number of glaciers, accumulation area ratio (AAR) method can be used. AAR is a ratio between accumulation area and total glacier area (Meier and Post, 1962). Accumulation area is an area of glacier above the equilibrium line. In temperate glacier, the extent of superimposed-ice zone is insignificant and therefore, equilibrium line coincides with the snow line (Paterson, 1998). Snow line at the end of ablation season and AAR can be estimated using remote sensing method (Kulkarni, 1992; Braithwaite, 1984).

To estimate glacial mass balance, a relationship between AAR and mass balance is developed using field mass balance data of the Shaune and the Gor Garang glaciers. Both of these glaciers are located in Baspa river basin. Field data was taken from various reports of Geological Survey of India (Singh and Sangewar, 1989). Glacier area was estimated using IRS LISS-III sensor which has spatial resolution of 23.5 m in visible and near infrared bands and 70 m in SWIR band. Images of July-September season (25 August 2001 and 11 September 2000) were selected, because during this period snow cover is at its minimum and glaciers are generally fully exposed (Kulkarni et al., 2002). Accumulation area for each glacier varies from year to year, and depends upon snow line at the end of ablation season. Snow line on glacier was monitored by systematically analyzing weekly data of WiFS and AWiFS sensor of IRS from May to October. It is ideally suited for snow cover monitoring due to 5-day repetitive coverage.

Mass balance was estimated in year 2001 and 2002 for 19 glaciers in the Baspa basin. AAR and specific mass balance was estimated for individual glacier. For each glacier, specific mass balance values were multiplied by area to obtain total loss on gain in glacial mass. Then mass balance of each glacier was added to assess total loss of glacial ice. The investigation suggests a loss of 0.2347 km^2 of glacial ice between 2000 and 2002. In addition, overall specific mass balance in hydrological year 2000-2001 and 2001-2002 were estimated as -90 and -78 cm, respectively. Orientation of glacier seems to have profound influence on snow line altitude. Average altitude of snowline at the end of ablation season is 5400 m for south and 5297 m for north facing glaciers. Area altitude distribution of glaciers also influences mass balance. As mid-altitude changes from 5000 to 5400 m, specific mass balances also changes from -111 cm to 49 cm.

This investigation has also shown that four glaciers in the Baspa basin are having no accumulation area and average snow line altitude is well above maximum glacial altitude. In addition, two glaciers are having very marginal accumulation area and their AAR is less than 0.01. These six glaciers are located in low altitude zone with average maximum altitude of 5266 m, which is almost 200 m less than the mean snow line of the basin. Satellite data suggests excessive debris cover on these glaciers, which are likely to experience relatively less melting; however, due to lack of formation of new ice, glaciers might experience terminal retreat.

Remaining glaciers are north facing and therefore, these are having a relatively lower snow line at the end of ablation season. In addition, average maximum altitude is also relatively higher, as these glaciers are located on northern slopes of Pir Panjal mountain range. Combination of higher area-altitude distribution and lower snow line makes higher accumulation area ratio. The difference between average snow line of north and south facing glaciers was observed to be 160 m. Glaciers located on northern slope in altitude region below 5170 m and 5330 m on southern slopes have very little or no accumulation area and experience terminal retreat.

MONITORING OF SEASONAL SNOW COVER

Himalaya has a large concentration of glaciers and permanent snowfields. During winters most of the high altitude region experiences snowfall and snow cover plays an important role in ecology of the region. Melting from seasonal snow cover during summer time forms an important source of many rivers originating in the higher Himalaya. Therefore, understanding of snow accumulation and ablation are important for utilization of the Himalayan water resources.

In order to estimate seasonal snow cover WiFS and AWiFS images were used. A combination of supervised and visual interpretation technique was used to interpret WiFS images and while the Normalised Difference Snow Index (NDSI) method was used to interpret AWiFS images (Kulkarni et al., 2002; Kulkarni et al., 2006).

NDSI is estimated using the following equation:

$$\text{NDSI} = \frac{[\text{Green Reflectance (B2) - SWIR Reflectance (B5)}]}{[\text{Green Reflectance (B2) + SWIR Reflectance (B5)}])}$$

To estimate NDSI, digital number values (DN) were converted into reflectance. The various parameters needed for estimating spectral reflectance are maximum and minimum radiances, mean solar exo-atmospheric spectral irradiances in the satellite sensor bands, satellite data acquisition time, solar declination, solar zenith, solar azimuth angles and mean Earth-Sun distance (Markham and Barker, 1987 Srinivasulu and Kulkarni, 2004). NDSI values for different major land features were obtained by using AWiFS data of December 17, 2003.

In optical region snow reflectance is higher compared to other land features as grass, rock and water. However, in SWIR region snow reflectance is lower than rock and vegetation. This characteristic can be effectively used to develop NDSI for snow cover mapping. Both of these bands are available in AWiFS sensor on Resourcesat, an Indian remote sensing satellite. For each pixel, NDSI values are obtained and each pixel is classified as snow, if NDSI value is greater than 0.4. Sensitivity analysis and field investigations were carried out to assess correct value of NDSI representing snow. The investigation suggests that this technique can also classify water pixels as snow. Therefore, to remove water pixels, mask of water body was used. This is a useful technique for the Himalayan region, as it can also be applied under mountain shadow condition. This is possibly due to reflectance from diffuse radiation in shadow areas. Therefore, an algorithm was developed to provide changes in areal extent of snow at an interval of 5-days and 10-days. In 5-daily product, snow extent is generated scene wise. In 10-daily product, three scenes are analyzed and basin-wise estimate of maximum snow extent is obtained.

In Baspa basin, areal extent of snow cover was monitored from October 2004 to June 2005 using AWiFS data of Resourcesat. A total of 49 scenes were analyzed and twenty one 10-daily products were generated. A graph giving accumulation and ablation of seasonal snow is given in Fig. 12 and 10-daily snow cover product giving areal extent of seasonal snow for October and November months in Fig. 13.

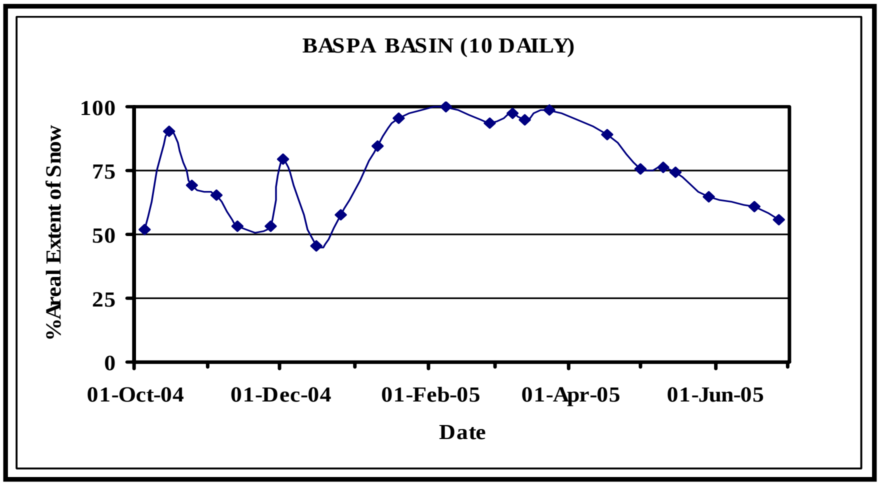

Fig. 12 Snow accumulation and ablation curve for Baspa basin, H.P.

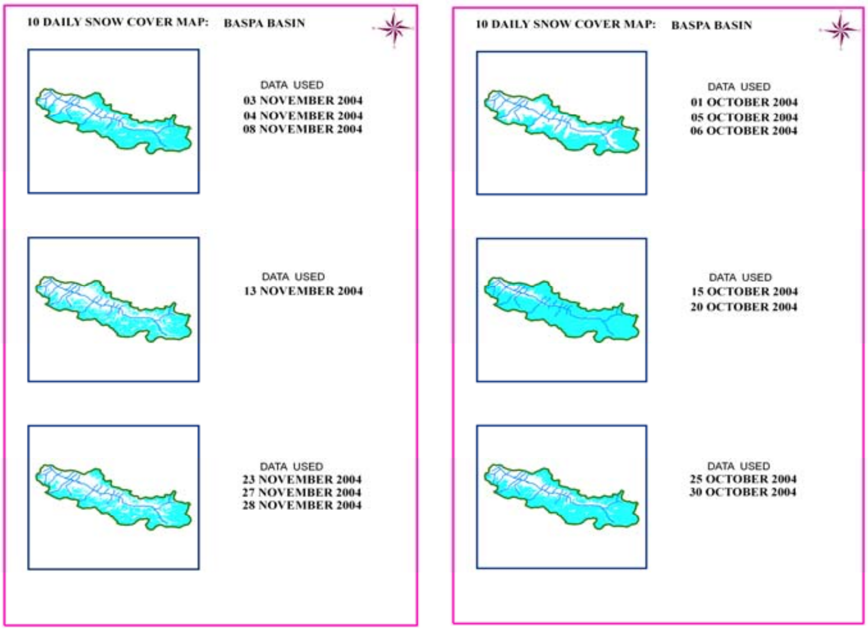

Fig. 13 Snow cover products of October and November months, Baspa basin, H.P.

Snow accumulation and ablation curve suggests, in early part of winter, i.e. from October to December end, large amount of snow can melt. This observation is consistent with earlier observations made in year 2000 and 2001. Altitudes ranging from 3000 to 4800 m at an interval of 600 m were monitored. From November to February, snow retreat was observed in all altitude zones.

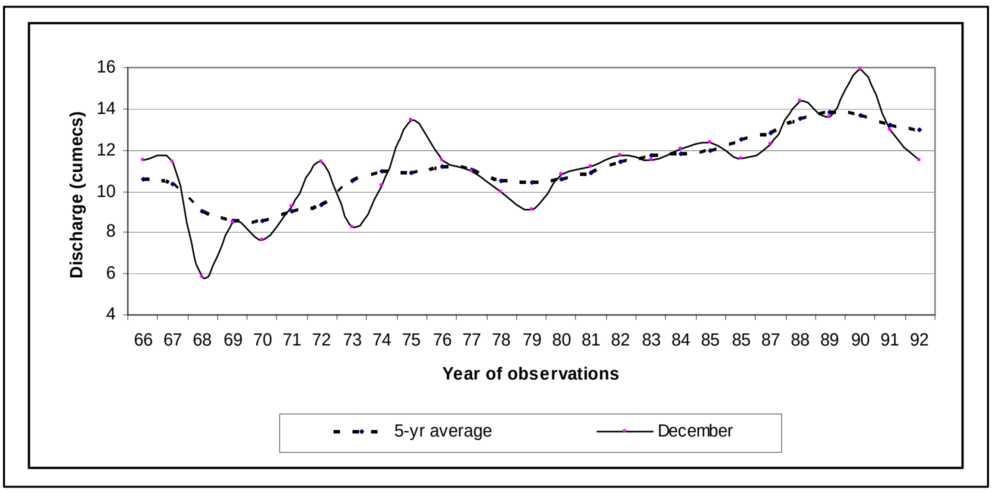

Fig. 14 Average stream runoff of Baspa river for December from 1966 to 1992.

Similar observations were also made in Beas basin (Kulkarni et al., 2002). However, this data is not long enough to assess long term changes in snow accumulation and ablation pattern of the Himalayan region. If, snow ablation pattern is changing, then this will have influence of stream runoff of Baspa river. Therefore, average stream runoff of the Baspa basin for the month of December is plotted form 1966 to 1992 (Fig. 14). Stream runoff between the periods of observation has gone up by 75%. This is a substantial rise in stream runoff, suggesting influence of climate change on Himalayan cryosphere.

CONCLUSIONS

In this paper effect of climate change on Himalayan cryosphere has been discussed. Two main components of cryosphere as glaciers and seasonal snow cover are included in this investigation. Numerous satellite sensors and field investigations were used to develop methodology and to assess results obtained from remote sensing technique. Loss in glacier area was estimated using high and medium resolution of satellite data and topographic maps of the Survey of India. In this investigation glacial retreat was estimated for 466 glaciers in Chenab, Parbati and Baspa basins since the year 1962. Expeditions to Chhota Shigri, Patsio and Samudra Tapu glaciers in Chenab basin, Parbati glacier in Parbati basin and Shaune Garang glacier in Baspa basin were organized to identify and map glacial terminus. The investigation has shown an overall reduction in glacier area from 2077 km^2 to 1628 km^2 since 1962, an overall deglaciation of 21%. However, number of glaciers has increased due to fragmentation. Mean of glacial extent was found to reduce from 1.4 to 0.32 km^2 between 1962 and 2001. In addition, number of glaciers with higher a real extent has reduced and with lower a real extent has increased between the period. Small glaciarates and ice fields have shown extensive deglutination. For example, 127 glaciarates and ice fields less than 1 km^2 have shown retreat of 38% since 1962, possibly due to their small response time. Another important parameter is glacier mass balance. Glacier mass balance was estimated using AAR method. The investigations suggest a loss of 0.2347 km^3 of glacial ice between 2000-2002. The overall specific mass balance in hydrological year 2000-2001 and 2001-2002 was estimated as -90 and -78 cm, respectively.

Seasonal snow cover is an important component of the Himalayan cry sphere. A NDSI based algorithm was developed to estimate seasonal snow cover. This monitored was carried out in Baspa basin, Himachal Pradesh in early part of winter, i.e. from October to December end, and a large amount of snow retreat was observed. In addition, average stream runoff of the Baspa basin for the month of December was found to increase by 75%. This combination of glacial retreat, negative mass balance, early melting of seasonal snow cover and winter time increase in stream runoff suggest an influence of climate change on Himalayan cryosphere.

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