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## Variations in snow cover and snowline altitude in Baspa Basin

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The Himalayas has one of the largest concentrations of glaciers and permanent snowfields outside the polar region. Snow and glacier melt forms an important source for many rivers originating in the Himalayas. Numerous studies suggest that global warming has started affecting snow melt and stream run-off in the Himalayan region. Monitoring the snow-cover changes is therefore essential to assess the future hydrologic cycle. Snowline altitude is an important parameter to assess future changes in snow cover. Variations in snowline altitude and snow cover for the years 2004–05 and 2006–07 between October and June for Baspa River Basin located in the Kinnaur District, Himachal Pradesh are reported here. The snow cover was delineated using 54 images of AWiFS sensor of Resourcesat-I satellite using NDSI technique and elevation information was generated using SRTM data. About 98% of the basin area is located below the elevation of 5800 m. The average monthly snowline altitude was estimated. The lowest snowline altitude was

observed as 2425 m in February 2004–05 and 2846.25 m in March in 2006–07.

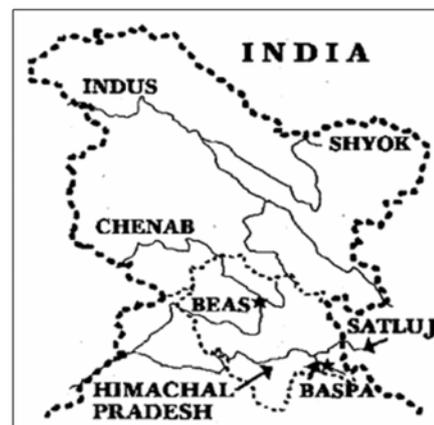
**Keywords:** Baspa Basin, global warming, snow cover, snowline.

THE Himalayas is one of the youngest mountains in the world and accounts for almost 70% of non-polar glaciers. The Himalayan region has permanent snow fields and in winter most of the high-altitude regions experience snow-fall<sup>1</sup>. During summer, snow melt is the major run-off for many rivers originating from the Himalayas, the lifeline of millions of people. Therefore, monitoring the changes in snow-cover area is essential not only for the development of ecosystems, but also for human activities like agriculture, hydropower generation, etc. Snow cover is highly dynamic and has a great influence on the local climate due to high albedo.

During the 20th century, the rapid industrialization caused a huge increase in global temperature by changing the composition of the atmosphere with large emissions of CO<sub>2</sub>, other trace gases and aerosols<sup>2</sup>. By 2100, the global surface temperature is projected<sup>2</sup> to increase by 1.4–5.8°C. The Intergovernmental Panel on Climate Change (IPCC) has estimated that with increasing level of global warming, regions receiving snowfall will increasingly receive precipitation in the form of rain and for every 1°C increase in temperature<sup>3</sup>, the snowline will rise by about 150 m.

The snowline is a line that divides the snow-cover surface and the barren surface at a given point of time<sup>4</sup>. The snowline is an important indicator of snow coverage and when viewed over a large area, the elevation shift of the snowline indicates a certain climate behaviour, either to a cold or a warm climate. A periodical study of the spatial-temporal variations of the snowline can help in assessing the hydrologic cycle balance as well as to understand the regional and global climatic changes.

The Baspa River Basin, a major tributary of the Satluj river, is located in Kinnaur District, Himachal Pradesh.



**Figure 1.** Location map of Baspa Basin, Himachal Pradesh, India.

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The river originates at Arsomang and Baspa Bamak glaciers and travels 72 km through the valley before joining the Satluj river at Karcham. The location map of the Baspa Basin is given in Figure 1. The basin is highly glacierized and located in the higher-altitude range, and the winter run-off of the Baspa Basin is mostly contributed by snow melt rather than rainfall<sup>1</sup>. In socio-economic terms, the Baspa Basin is important as many mini and micro hydropower stations are being planned in this basin. Earlier studies have shown that average stream run-off of the Baspa river in the month of December has gone up by 75% between 1966 and 1992 due to snow melt<sup>1</sup>. Therefore, it is important to monitor the variations in snowline altitude for the Baspa Basin.

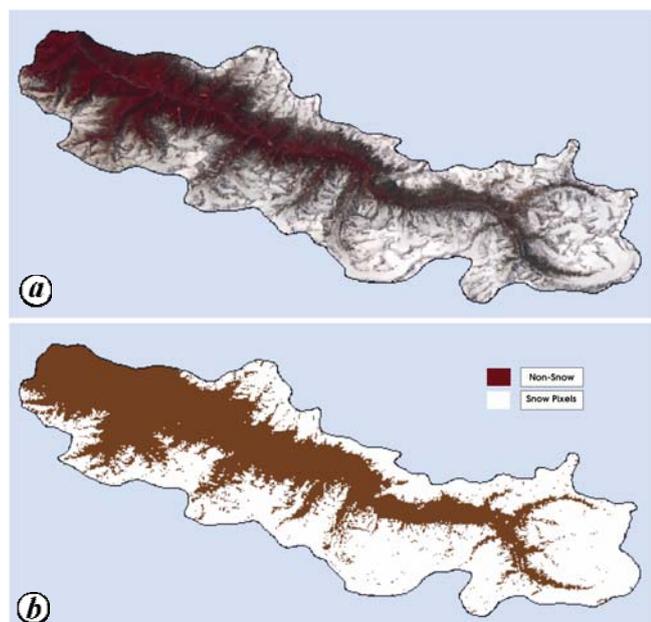
It is difficult to make periodic observations of snow cover and snowline in the Baspa Basin using field methods due to its high altitude and harsh environmental conditions. In the last few decades, advancement in the field of remote sensing has made it as one of the valid and powerful sources of data, enabling periodical assessment and monitoring of the natural resources with its continual improvement of spatial, spectral and temporal resolution.

Satellite remote sensing offers the opportunity to monitor and evaluate various snow parameters and processes at regional and global scale<sup>5,6</sup> and the remote sensing technique has been used extensively for snow-cover monitoring in the Himalayan region with the help of numerous satellite sensors<sup>7</sup>. Geographical Information System (GIS) along with remote sensing technology facilitate fast and efficient ways to analyse, visualise and report the seasonal snow-cover changes. Investigation of snow-cover and snowline variation in Baspa Basin was carried out

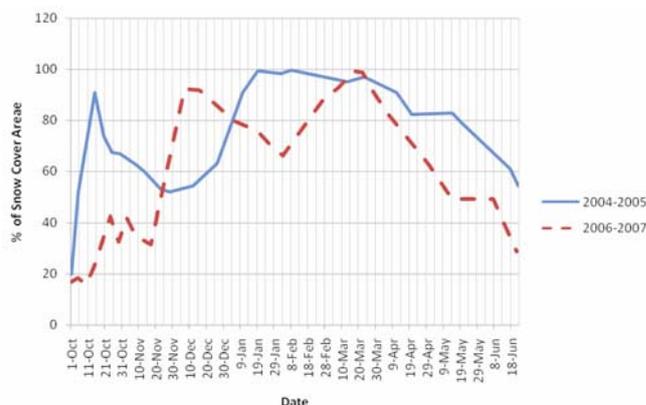
using remote sensing and GIS techniques. The major difficulty in snow-cover monitoring using an automated technique in the Himalayan region is the mountain shadow and confusing signature of snow and cloud in the visible and near infrared region. Normalized Difference Snow Index (NDSI) method effectively addresses this issue and has advantages when compared to the supervised and hybrid techniques, as it can detect snow even under mountain shadow and is not influenced by topographic conditions<sup>8</sup>. This is an effective index for mapping snow cover in rugged terrain<sup>9</sup>. The availability of green and SWIR bands enables the AWiFS sensor data for identification of snow-covered areas applying the NDSI technique. The AWiFS sensor of Resourcesat-1 has high saturation radiance, large swath of about 740 km, 56 m spatial resolution and 5 days temporal resolution<sup>10</sup>.

Initially, the AWiFS images were properly geocoded. Then the images were clipped exactly to the basin boundary using vector basin boundary layer. A total of 54 scenes were analysed for the period between October and June for the years 2004–05 and 2006–07. The binary snow-cover images were generated from these images by applying the NDSI method<sup>8</sup>, with a threshold value of >0.4. The AWiFS image and the snow cover identified by the NDSI method are shown in Figure 2 *a* and *b* respectively, and the snow-cover accumulation and ablation curve is generated as shown in Figure 3.

The area elevation curve for the Baspa Basin was generated using the 100 m interval vector isolines derived from the SRTM digital elevation data. The Shuttle Radar Topography Mission (SRTM) digital elevation dataset provides a global coverage of the earth's land surface with 90 m spatial resolution and ± 15 m vertical accuracy. A semi-automated tool was developed in the modeler environment of the ArcGIS 9.2 software for calculating the area-elevation distribution. This tool takes contours and basin boundary vector layers as inputs and generates the output elevation zones and a table summarizing the area-elevation distribution of the basin. The



**Figure 2.** *a*, AWiFS sensor data for 14 May 2007. *b*, Snow pixels identified by NDSI method from AWiFS sensor data for 14 May 2007.



**Figure 3.** Snow cover area for the periods October 2004–June 2005 and October 2006–June 2007.

hypsothetic graph for the Baspa Basin prepared from the area-elevation distribution curve is shown in Figure 4.

In our approach, determination of snowline altitude for October–June during 2004–05 and 2006–07 was carried out using the area-altitude distribution curve and the snow-cover area. The snowline altitude for a particular date was calculated by selecting the elevation for which the cumulative percentage area of elevation zones is equal to the snow-cover percentage of the total area. The graph of mean monthly snow cover and snowline altitude is shown in Figures 5 and 6 respectively. From the area-elevation curve of the basin as shown in Figure 4, it was found that almost 70% of the basin area lies in the elevation range 4200–5700 m and 98% of the basin area is located below 5800 m, while the total elevation range observed is from 1900 to 6400 m. The altitude covering 50% of the basin area is 4800 m approximately. It has been inferred from the graph shown in Figure 3, that the snow-cover area for the year 2004–05 has remained higher than that for 2006–07, with exceptions during the periods 25 November 2006 to the first week of January 2007, and 10 to 25 March 2007. On comparing the snow

cover between 2004–05 and 2006–07 for the months of October to the first fortnight of March, no pattern was observed. But a steady depletion of the snow cover began at the end of March and continued till June for both the years. The depletion of snow cover during April–June 2007 was more compared to April–June 2005. Figures 5 and 6 suggest that the mean snow-cover area in March 2005 and 2007 was approximately 96%; but the mean snow-cover area in June 2007 was 39%, which is less by 18% compared to June 2005. The mean snow-cover area during October 2006–June 2007 decreased by 14.4% compared to 77.06% observed for the period October 2004–June 2005. The mean snowline altitude for June 2007 was 5000 m, which is 420 m higher than in June 2005. The snowline altitude loss value for a month was calculated by finding the difference between its snowline altitude and that of the previous month.

The average monthly snowline altitude loss for the period April–June 2007 was 718 m, which is 167.33 m higher than in 2005. In addition, an increase in the mean snowline altitude by 500 m was observed for 2006–2007.

Snowpack ablation is highly sensitive to climatic variations. Increase in atmospheric temperature can enhance

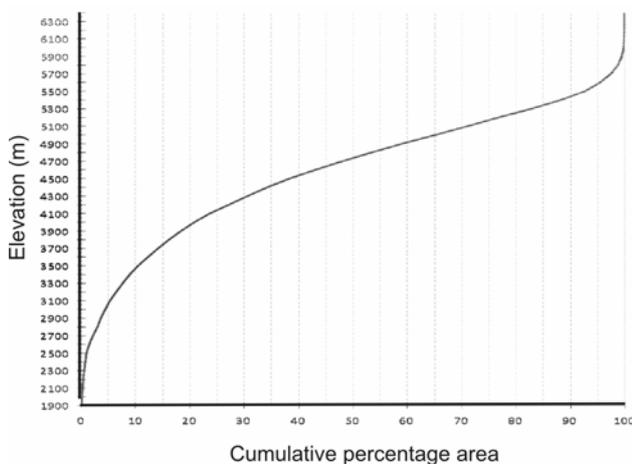


Figure 4. Area altitude distribution curve for the Baspa Basin.

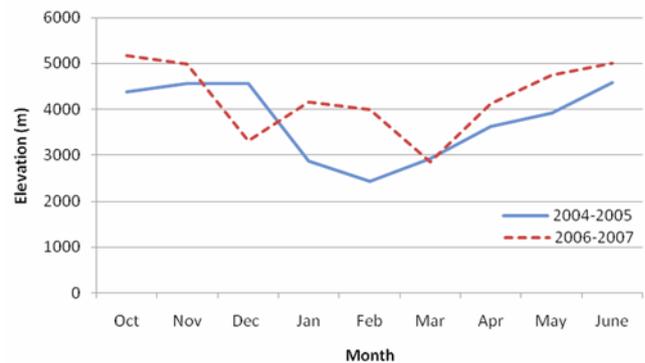


Figure 6. Snow line altitude for the periods October 2004–June 2005 and October 2006–June 2007.

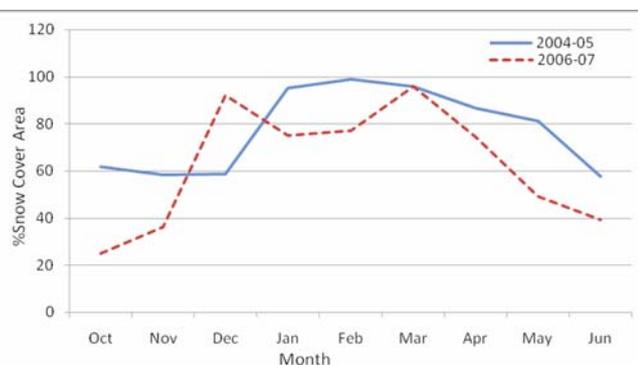


Figure 5. Mean monthly snow-cover area for the periods October 2004–June 2005 and October 2006–June 2007.

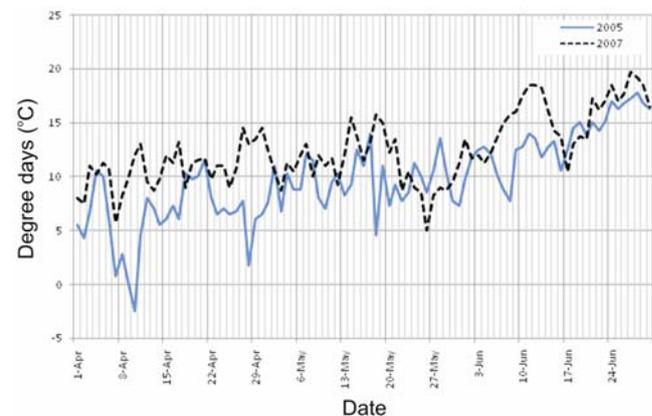


Figure 7. Variation in number of degree days from April to June for the years 2005 and 2007.

energy exchange between the atmosphere and snowpack. This can increase snow melting. Field data such as temperature have been used in this investigation. Daily maximum and minimum temperatures at Raksham were used to estimate mean maximum and minimum temperatures for the ablation season. The mean temperatures were used to estimate average degree days for April–June during the period 2005–07. The number of degree days (in °C) was determined as  $T = (T_{\max} + T_{\min})/2$ . The number of degree days was highly correlated with snowmelt<sup>11</sup>. Figure 7 suggests that number of degree days during the year 2007 is substantially higher compared to 2005.

Available temperature data confirm the decrease in snow-cover area and increase in snowline altitude during the ablation season and subsequently increasing the snow melt. In relation to previous studies carried out in the Baspa Basin<sup>1</sup>, this study confirms that the run-off to the Baspa stream is primarily increasing due to the rise in snow melt during the ablation season. Thus the study of snow cover and snowline in the Baspa Basin indicates the depletion of snow pack and the subsequent rise in snowline.

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## Modelling of BSRs as prime indicator of gas hydrates

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To understand the complex phenomena associated with the formation of bottom simulating reflector (BSR), the main identifier for the presence of gas hydrate, we have generated synthetic responses of different seismic velocity (hydrate-free gas) models to draw meaningful reflection characteristics. The synthetic response of the model of high-velocity (hydrated) sediment layer underlain by low-velocity free-gas layer indicates a normal polarity reflector generated at the top edge of the hydrated layer and a strong reverse polarity reflector (BSR) at the interface of hydrated/free-gas layer (base of the gas hydrate). The synthetic response of high-velocity hydrated layer sandwiched in the normal oceanic sediments produces reversely polarized reflector at its base (BSR). The BSR is quite distinguishable when the acoustic velocity of hydrated sediments is appreciably high. Model studies indicate that high-amplitude reverse polarity reflector (BSR) can be generated with only the presence of low-velocity (free-gas) layers overlain by normal sediments at a depth of a few hundred metres below the seafloor. There is appreciable increase in the strength of this reflector with lowering of velocity free-gas layer. The studies indicate that BSR may be generated in most of the cases where a strong impedance contrast exists due to either high-velocity gas hydrates or free-gas layer, and hydrates underlain by free-gas. Out of all three different configurations, hydrates underlain by free-gas produce BSRs with higher strength. The results from drill sites where BSRs were not found associated with gas hydrate may indicate that the BSR might have been produced due to the presence of free-gas only. Places where gas hydrate has been found without BSR may suggest that the gas hydrate may occur in lenses or very thin layers, not giving rise to appreciable impedance contrast for the generation of the BSR.

**Keywords:** Bottom simulating reflectors, gas hydrates, impedance contrast.

GAS hydrates with high estimated reserves are being projected as viable alternatives to fill the gap of the ever-increasing demand for conventional fossil fuel resources. Seismic reflection method is one of reliable techniques for the exploration of gas hydrates. The impedance contrast created by the presence of gas hydrate (high velocity)

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