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The effect of black carbon on reflectance of snow in the accumulation area of glaciers in the Baspa basin, Himachal Pradesh, India

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Abstract

Himalayan glaciers are being extensively debated in scientific and public forums, as changes in their distribution can significantly affect the availability of water in many rivers originating in the region. The distribution of glaciers can be influenced by mass balance, and most of the glaciers located in the Pir Panjal and Greater Himalayan mountain ranges are losing mass at the rate of almost a meter per year. The Equilibrium Line Altitude (ELA) has also shifted upward by 400 m in the last two decades. This upward migration of ELA and the loss in mass could have been influenced by changes in temperature, precipitation and by the deposition of black carbon in the accumulation area of glaciers. The deposition of black carbon can reduce the albedo of snow in the accumulation area leading to faster melting of snow and causing more negative mass balance. In this investigation, a change in reflectance in the accumulation area of the Baspa basin is analysed for the year 2009, as the region has experienced extensive forest fires along with northern Indian biomass burning. The investigation has shown that: (1) The number of forest fires in the summer of 2009 was substantially higher than in any other year between 2001 and 2010; (2) the drop in reflectance in the visible region from April to May in the accumulation area was significantly higher in the year 2009 than in any other year from 2000 to 2012; (3) the temperature of the region was substantially lower than the freezing point during the active fire period of 2009, indicating the small influence of liquid water and grain size; (4) the drop in reflectance was observed only in the visible region, indicating role of contamination; (5) in the visible region, a mean drop in reflectance of 21 ± 5 % was observed during the active fire period in the accumulation area. At some places, the drop was as high as 50 ± 5 %. This can only be explained by the deposition of black carbon. The study suggests that a change in snow albedo in the accumulation area due to the deposition of black carbon from anthropogenic and natural causes can influence the mass balance of the glaciers in the Baspa basin, Himachal Pradesh, India.

1 Introduction

Himalayan glaciers are being discussed extensively, as they can affect the supply of water to a large number of people in the Indian subcontinent. Numerous investigations were carried out in the Himalayan region to understand the loss in glacier area and estimates for almost 6000 glaciers covering an aerial extent of 20 000 km^2 are available. This is almost half of the glacier-covered area in the region and it suggests that the glaciers are losing an average 0.4 % area per year (Bolch et al., 2010, 2012; Yong et al., 2010; Bhambri et al., 2011; Kamp et al., 2011; Kulkarni et al., 2011; Bahuguna, 2007). This is a general trend and the loss in area is different in different parts of the Himalayan region. Some large glaciers in Karakoram are stable or advancing (Scherler, 2011). However, assessments based on length measurements could be misleading, as recent investigations have shown that even if the glaciers are losing the same amount of mass, their retreat could be influenced by slope and length (Venkatesh et al., 2012). In addition, if the lower regions of the glaciers are covered by debris, then it would retard retreat and may lead to the fragmentation of the glaciers (Kulkarni et al., 2007). Therefore, it would be useful to understand the changes in glacial mass to assess future changes in glacial extent.

One of the key parameters, which can influence the future distribution of glaciers and the availability of water, is mass balance. Measurements of the mass budget for glaciers in the Himalayan region are relatively few and only for a short duration. The available data suggest that the mass budget over the larger part of the Himalayas was negative over the past decades and the rate of loss increased after 1995 (Sangewar and Kulkarni, 2011; Dhobal et al., 2008; Haeberli et al., 2001). The loss in mass for many small glaciers located in a low altitude range could be as high as 1 $m\,yr^{-1}$ in thickness. This is a substantial loss considering that the mean depth of the small glaciers could be between 30 and 50 m (Raina and Srivastava, 2008). These small glaciers and ice fields are an important source of water for many mountain communities. By considering small volume and large mass loss, this source of water could be significantly

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influenced in the near future and could affect the sustainability of many mountain communities. The mass balance of numerous glaciers located in the lower ranges of the Himalayas, such as Pir Panjal and the Greater Himalayas, could also be significantly affected due to the deposition of black carbon on the accumulation area in addition to changes in temperature and precipitation.

The Himalayan region may experience a warming trend due to the additional absorption of solar radiation due to an aerosol brown cloud (Chand et al., 2009; Sateesh et al., 2008). This may also influence the albedo of snow and glaciers due to the deposition of light-absorbing aerosols on them. This can influence the pattern and availability of seasonal snow and glacier melt. Atmospheric brown clouds are generally formed due to biomass burning and fossil fuel consumption. Previous studies have demonstrated the influences of the springtime northern Indian biomass burning over the central Himalayas (Kumar et al., 2011). They consist of a mixture of absorbing and scattering aerosols, leading to atmospheric heating and surface cooling. However, some models suggest that over a snow/ice surface, where the albedo is close to 1, the cooling is negligible and the warming effect of absorbing aerosols is the largest (Ramnathan et al., 2007). In addition, a threefold increase in aerosol optical depth was observed from 1985 to 2000 (Satheesh et al., 2002, 2009; Moorthy et al., 2009). During summer and the pre-monsoon periods atmospheric boundary layer dynamics play an important role in transporting the aerosols from the valleys to higher levels (Pant et al., 2006). This can cause additional warming at higher altitudes, influencing glacier melt. In addition, if aerosols are deposited on the snow/glacier cover, they can influence the albedo. A small amount of BC aerosols from 120 to 280 ppbw can reduce the snow albedo by 4 to 8 % in the visible region. This combination of a rise in temperature and reduction in the albedo will have a significant influence on snow and glacier melt (Hansen and Nazarenko, 2004). In the year 2009, an unusually large number of forest fires were reported in the hills of the Western Himalaya and this investigation reports the influence of unusual forest fires on the snow albedo in the accumulation area of glaciers in the Baspa basin.

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2 Study area and data

The investigation was carried out in the Baspa basin in Himachal Pradesh (Fig. 1). This basin was selected because glaciers in this basin have been well mapped and studied (Kulkarni and Alex, 2003). In addition, the relationship between the Accumulation Area Ratio and the mass balance is well established (Kulkarni, 1992; Kulkarni et al., 2004).

The satellite data of the AWiFS sensor of the Indian Remote Sensing Satellite and MODIS land surface products were used. The MODIS surface reflectance and fire data products were collected from http://earthexplorer.usgs.gov/ site. The AWiFS images of 14 April, 27 May and 20 June of year 2009 were analyzed to estimate reflectance. The sensor specifications in detail are given in Kulkarni et al. (2006). The single day MODIS surface reflectance product from 10 to 15 April and 1 to 5 May between the years 2000 to 2012 were used to assess the mean changes in reflectance due to aging.

The elevation data of Aster DEM (version 1) of 30 m spatial resolution were used in the study. Temperature and snow fall data were collected from the Bhakra Beas Management Board. The location of the Kaza observatory is given in Fig. 2 and the altitude is 3600 m. Information about the area affected by forest fires in Himachal Pradesh was collected from the Department of Environment, Science and Technology, Government of Himachal Pradesh. The duration of the forest fires was collected from numerous sources like newspaper reports, MODIS burned area products and satellite images.

Spectral reflectance data collected in the adjacent Beas basin were used in the investigation to understand the relative influence of soil and BC contamination on the reflectance of snow. Detailed information about the field setup, and the instruments and methodology of data collection are given in Singh et al. (2011). The reflectance data were collected for the spectral region between 350 and 2500 nm at an interval of 10 nm. The reflectance for the green band was estimated by integrating reflectance between 520 and 590 nm, which is the spectral band width of band 2 in the AWiFS sensor.

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3 Methodology

The MODIS land surface reflectance products were used to estimate changes in reflectance between April and May. Single day products from 10 to 15 April and 1 to 5 May were initially manually screened for a cloud cover. Later, the mean reflectance of snow in the accumulation area was estimated for a period between 10 to 15 April and 1 to 5 May. The difference in reflectance between these two periods was used to estimate changes due to aging processes. This period was optimized by considering forest fires in the year 2009 and snowfall events in other years. Therefore, further investigations were carried out using better resolution AWiFS sensor of the Indian Remote Sensing Satellite.

Raw AWiFS data are normally available in the form of Digital Numbers (DN) and need to be converted into a radiance value using sensor calibration. Atmospheric correction was carried out using the dark object subtraction (DOS) model (Negi et al., 2009a). The reflectance of each AWiFS band was derived directly from atmospheric corrected radiances (Dozier 1984);

$$\rho_\lambda = \frac{\pi \cdot L_\lambda \cdot d^2}{\mathrm{Esun}_\lambda \cdot \cos\theta_0} \tag{1}$$

where ρ_λ is the reflectance of a pixel, L_λ is atmospheric corrected spectral radiance from the pixel, d is the earth-sun distance, Esun_λ is mean solar exo-atmospheric spectral irradiance and θ_0 is the solar zenith angle. In order to understand the effect of topography, topographic corrections are essential as the snow cover in the Himalayas lies on the mountains. Negi et al. (2009a) used different topographic normalization techniques such as cosine-correction, C-correction and Minnaert-correction and found that these methods can introduce overall uncertainties up to ±5 %. We have applied the cosine correction method for topographic normalization, as this is a common and simplest correction method which can make rapid operational retrievals (Srinivasulu and Kulkarni, 2004).

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The reflectance estimated depends on the illuminating and viewing geometries i.e. zenith and azimuth angles of the sun and sensor. To characterize the anisotropic reflectance of snow, the spectral albedo i.e. directional hemispherical reflectance and bi-hemispherical reflectance was estimated using the application of asymptotic radiative transfer (ART) theory. This technique was used by Negi and Kokhanovsky (2011a, b) to retrieve the spectral albedo for Himalayan snow. Since this theory is only valid for weakly absorbing snow layers, the spectral albedo was retrieved for the first three bands of AWiFS data (Negi et al., 2011). The solar zenith angle (SZA), solar azimuth angle (SAA), sensor zenith angle (VZA) and viewing azimuth angle (VAA) for each pixel were calculated from the leader file of the imagery. In this study, due to the mountainous terrain of the Himalaya, the values of the different angles were estimated in the form of a local incidence angle and local viewing angle. This was calculated for both sun and sensor geometry using local incidence angle equations. This takes care of different slopes as well as aspects of the terrain. To identify a snow pixel, a criterion was made using a normalized difference snow index (NDSI) and reflectance at the visible wavelength band. A threshold value of the NDSI was used as 0.6, with the condition that the Green channel reflectance be greater than 0.5 to avoid fractional snow cover.

4 Results

The state of Himachal Pradesh in India experienced an unusually high incidence of forest fires in the summer of 2009. The forest fires were active in the month of May 2009, and widespread light to moderate rain on 11 June 2009 doused the forest fires. These forest fires were active in various regions of Himachal Pradesh and the locations of some of the forest fires and the glaciated terrain of the Baspa basin are given in Fig. 2. The location and directions of the smoke plume were estimated using Landsat 5 TM Imagery of 18 May and 19 June 2009. The smoke plume was observed moving towards the glaciated terrain. The area affected by forest fires from the years 2001 to 2010, except for the year 2006, is given in Fig. 3. The area affected by forest fires in the

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year 2009 was almost three times higher than in normal years. In addition, the global fire information management system suggests that during the same time, a large area in the Indo-Gangetic plains in India and Pakistan was under agricultural fires. These forest and agricultural fires generated a large amount of Black Carbon and due to the prevailing wind, it migrated in a Northerly direction.

In this investigation, the spectral region between 0.52 and 0.59 µm is used, as this region is sensitive to contamination rather than grain size (Warren, 1982; Negi et al. 2009b; Singh et al., 2010). To estimate changes in reflectance, high altitude accumulation areas of the glaciers were selected (Fig. 4). This was important, as for the entire duration of the investigation, i.e. from 14 April 2009 to 20 June 2009; the region remained under a seasonal snow cover and all the pixels were within the accumulation area. If regions other than accumulation areas are selected, then a loss in the albedo could also be due to changes in the land cover from snow to rock, vegetation or ice. In this investigation, a geographical area of 36.6 km^2 was mapped. The total area under the glacier in the Baspa basin is 167 km^2 (Kulkarni and Alex, 2003).

Initially, MODIS land surface reflectance products were used to estimate changes in mean reflectance between 10 to 15 April and from 1 to 5 May. The investigation suggests that the mean drop in reflectance during this period, in the study area is 7 % for 12 yr starting from the year 2000. The drop in reflectance in the year 2009 is 27 % and is substantially higher than the mean and 2 standard deviation (i.e. 16%) (Fig. 5).

The monitoring of snow albedo using AWiFS was started on 14 April 2009, when the region had no forest fires and the snow at an altitude of 5000 m was fresh and clean. The mean spectral albedo of snow in the green band of the AWiFS sensor was observed to be around 83 ± 5 %. The forest fire started in the last week of April, and by the middle of May, the region experienced extensive forest fires. The next available satellite data were on 27 May. The spectral albedo declined in the green band and was found to be almost 62 ± 5 %. A loss in albedo of 21 ± 5 % is substantial. The reflectance estimates of a subsequent date on 20 June show a spectral albedo 60 ± 5 % (Fig. 6). Now the amount of reduction is low, even though the region continued to experience major forest fires. This is probably because previous investigations have shown that initial contamination has a larger effect on snow albedo than subsequent contamination of the same amount (Singh et al., 2011). The areal distribution of loss in green reflectance from 14 April to 20 June 2009 is plotted in Fig. 7 and the albedo change in other bands is given in Fig. 8. The mean loss in snow reflectance is 24 ± 5 % and in some regions, it is as high as 40 to 50 ± 5 %, during active forest fires.

Spectral reflectance observations carried out in the region under controlled conditions suggest that the accumulation of soil, which is predominantly mineral dust, of more than 1 mg cm^{-2} is needed to explain the drop in reflectance by 24 ± 5 %. A more than 50 % loss in reflectance cannot be explained by contamination of the soil (Fig. 9). Contamination of more than 1 mg cm^{-2} is unlikely in the month of April at accumulation areas at an altitude of more than 5000 m (Fig. 4). However, a very small amount of black carbon, i.e. around 0.37 mg cm^{-2} can reduce reflectance by the required number. In addition, the spectral albedo values retrieved on 27 May and 20 June (Fig. 8) are almost similar in the Green, Red and NIR bands and show a flat trend which is normally BC/soot presence in snow (Warren and Wiscombe, 1980; Negi et al., 2009b). Therefore, the loss in reflectance is possibly due to black carbon rather than mineral dust.

The daily temperature data were available at Kaza, which is in the same region, and at an altitude of 3600 m (Fig. 2). The temperatures were further adjusted using a lapse rate (Pratap Singh, 2002) for the altitude of the accumulation area and this suggest that temperatures in the study area were substantially lower than freezing point (Fig. 10), indicating that liquid water may not be a influencing factor in changing snow reflectance from 14 April to 27 May. Temperature data suggest that the region has experienced a sudden increase in temperature and temperatures were well above the melting point in the study area after 20 June 2009, indicating the melting of snow.

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5 Conclusions and discussions

Numerous Indian states such as Jammu and Kashmir, Himachal Pradesh and Uttarakhand, located in the Western and Central Himalayan region, experience large forest fires in the months of May and June. In addition, adjacent regions on the Indo-Gangetic plains also experience large agricultural fires. This can generate a large number of black carbon particles which may be transported into the glaciated terrain of the lower Himalayan mountain ranges due to a southerly wind. It can significantly affect the albedo of seasonal snow and on the accumulation areas of glaciers, as BC absorbs substantially more radiation than mineral dust.

This investigation suggests that in the summer of 2009, a substantially higher than normal area was affected by forest fires. This provided a unique opportunity to understand changes in the snow albedo in accumulation areas, caused by the deposition of BC. MODIS data suggest that the decrease in reflectance between 10–15 April and 1–5 May 2009 is 27 % ($> 2\sigma$) and is substantially higher than in any other year between 2000 and 2012. The investigations carried out using AWiFS data suggest a 21 ± 5 % loss in the spectral albedo in the green band during active forest fires, i.e. between 14 April and 27 May 2009. This is a substantial loss when considering that the altitude ranges of the study were between 5000 and 6000 m and the daily mean temperatures were below freezing point. At some places, the loss in reflectance was as high as 40 to 50 ± 5 %. This loss in reflectance cannot be easily explained by the contamination of mineral dust, as reflectance investigations carried out in this region suggest that a large concentration of mineral dust is needed to drop reflectance by ±40 %. In addition, the spectral albedo retrieved on 27 May and 20 June shows a flat trend which is an indication of snow contamination by Black carbon. This suggests that BC has a major role in the reduction of the reflectance of snow in the accumulation areas of glaciers in the Baspa valley. The reduction in the albedo of snow in early spring can lead to the early melting of seasonal snow, early exposure of the ablation area and a lower accumulation area. This could lead to more negative mass balance and BC could be

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one of the contributing factors in addition to changes in temperature and snow fall, for an observed mass loss of more than −1 m for glaciers located in this part of the Indian Himalayas, and also for an observed increase in ELA by 400 m from the years 1980 to 2007 (Pandey et al., 2012).

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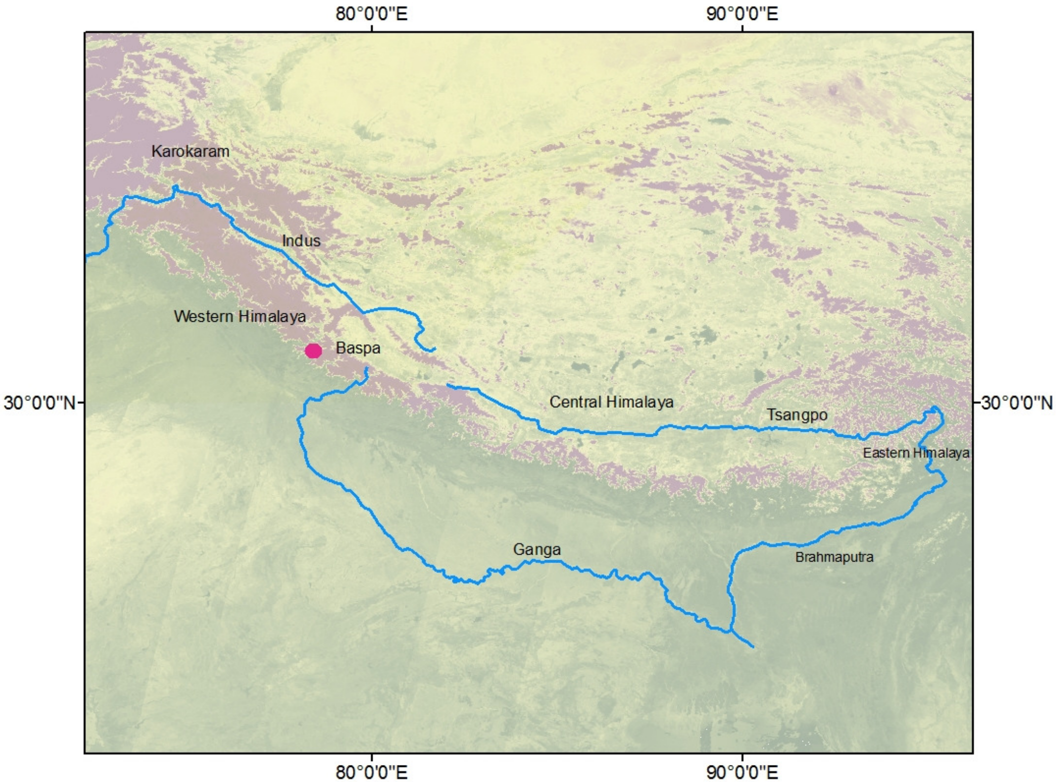

Fig. 1. Location map of the Baspa basin, a tributary of the Indus river in Himachal Pradesh, India.

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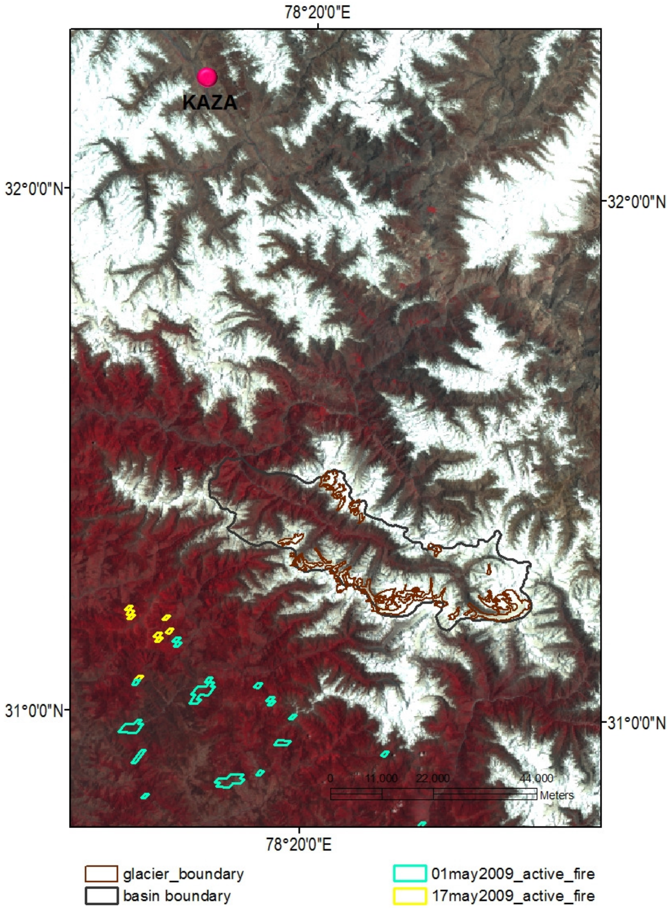

Fig. 2. Location of glaciers in the Baspa basin and active forest fires on 1 and 17 May 2009. Locations of active forest fires are taken from MODIS active fire products.

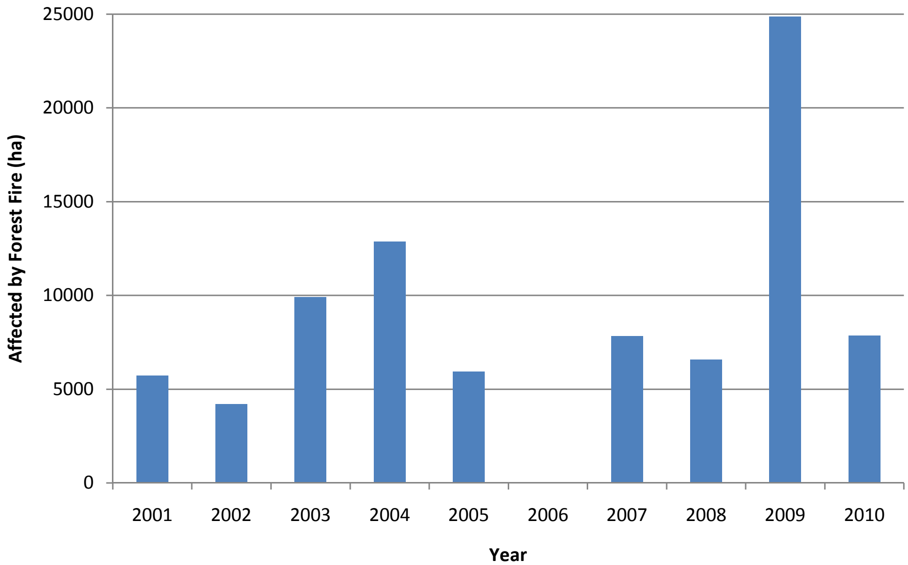

Fig. 3. The area affected by forest fires in the state of Himachal Pradesh, India. The areal extent of forest destroyed by fire in the year 2009 is substantially higher than in any other year between 2001 and 2010, except the year 2006, for which statistics are not available.

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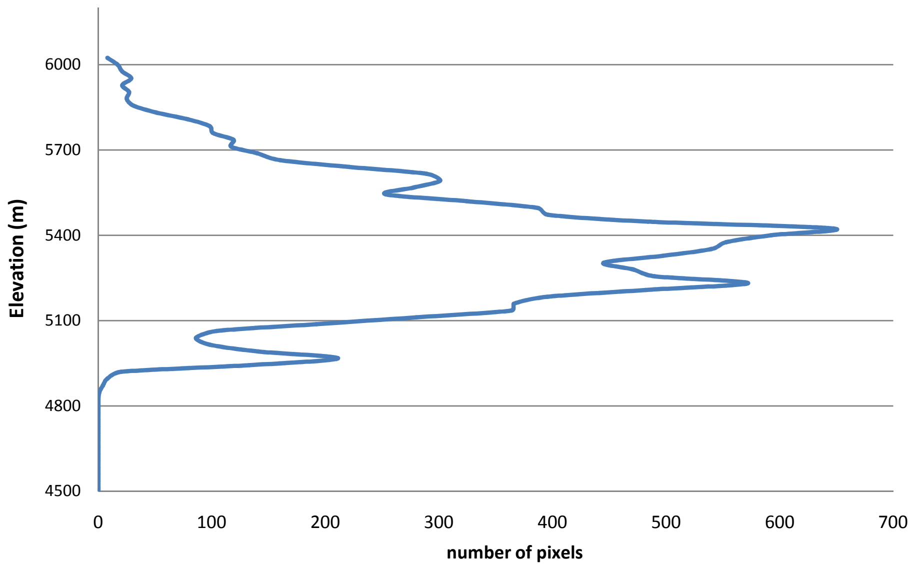

Fig. 4. The altitude distribution of pixels used in the investigation. The study area is predominantly above 5000 m and the area remained under a seasonal snow cover during the period of investigation.

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A. V. Kulkarni et al.

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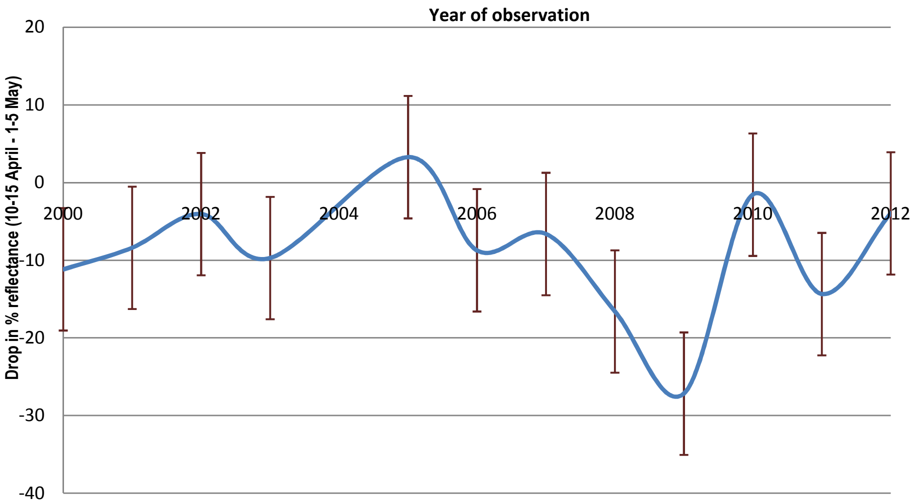

Fig. 5. Change in reflectance between 10–15 April and 1–5 May for the years 2000 to 2012. The change in reflectance for the year 2004 is not plotted, as the region has experienced unseasonal snow fall during the study period. The drop in reflectance in the year 2009 is 27 % and is higher than 2σ (16 %).

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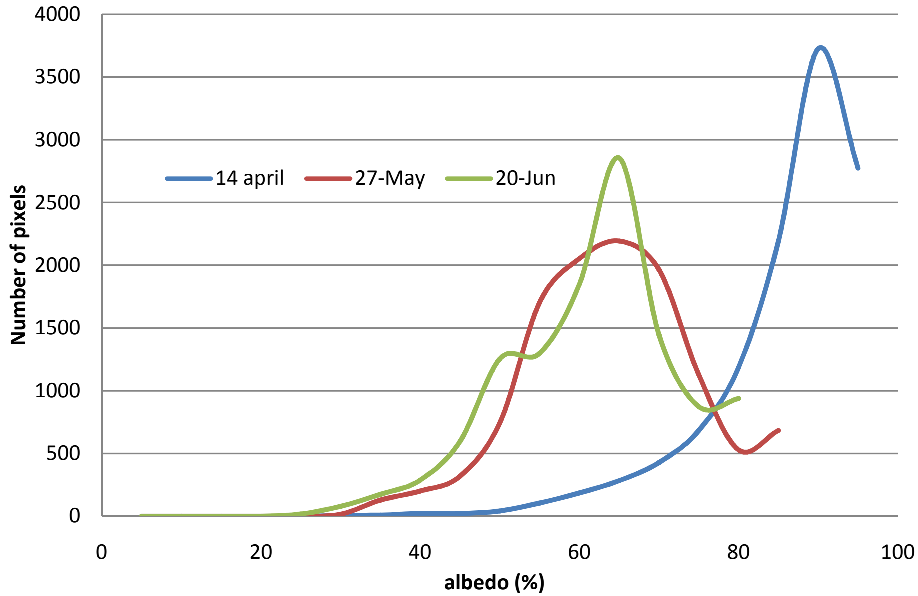

Fig. 6. Histographs showing the distribution of albedo of snow in the accumulation area of glaciers in the Baspa basin in band 2 (520–590 nm) of the AWiFS sensor.

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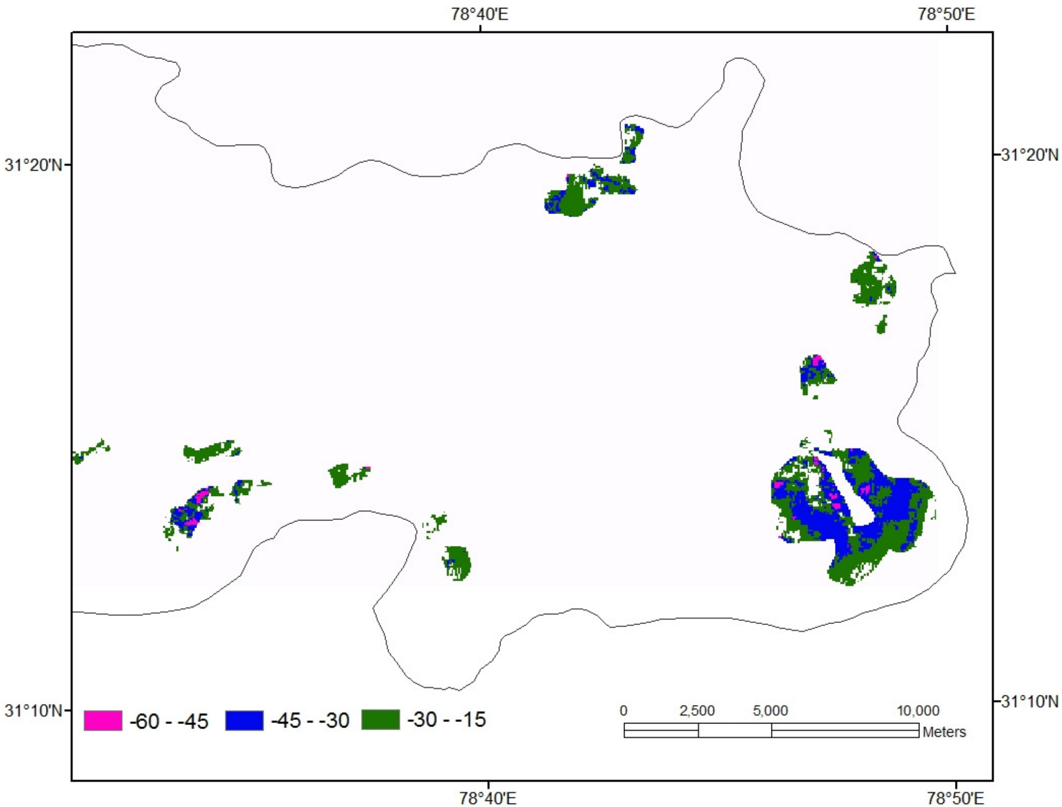

Fig. 7. Change in spectral albedo in the accumulation areas of Baspa basin between 14 April 2009 and 20 June 2009. The change in reflectance was estimated in the green band of the AWiFS sensor. The drop in reflectance between 60 to 15 % was observed.

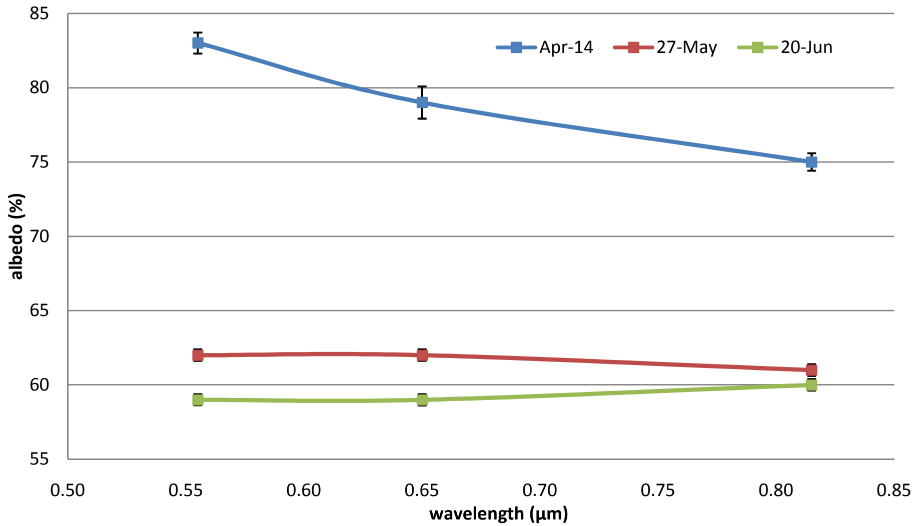

Fig. 8. The mean values of spectral albedo of the study area between 14 April 2009 and 20 June 2009. The spectral albedo was retrieved for first three bands of AWiFS data, as these are weakly absorbing snow layers. The difference in reflectance in bands 2, 3 and 4 is small on 27 May and 20 June as compared to 14 April 2009. This is indicative of snow contamination by Black carbon on 27 May and 20 June 2009. (Reference: Warren and Wiscombe, 1980; Negi et al., 2009b).

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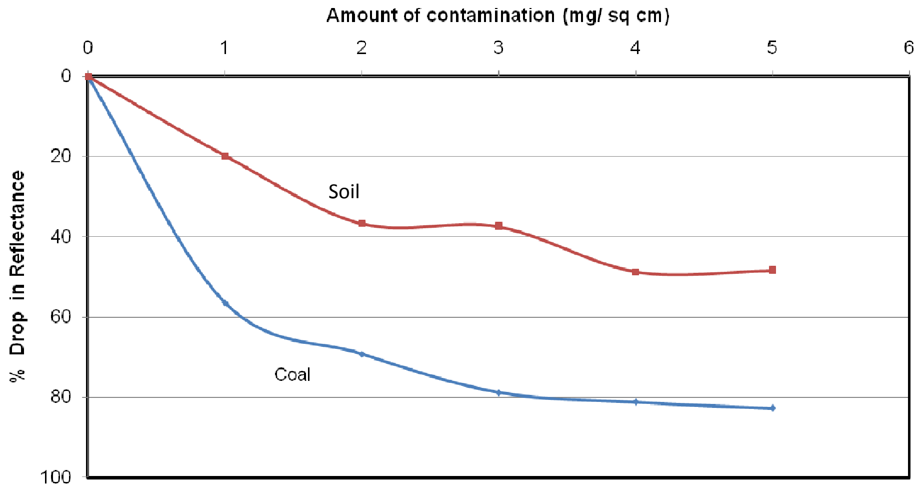

Fig. 9. The drop in reflectance due to an increase in contamination in the spectral region between 0.52 and 0.59 µm is plotted. The influence of BC contamination is substantially higher than that of soil, which was dominated by mineral dust. The graph suggests that the loss in snow reflectance by 24 ± 5 % from 14 April to 20 June 2009, during active forest fires is too large to be explained by any contamination other than black carbon.

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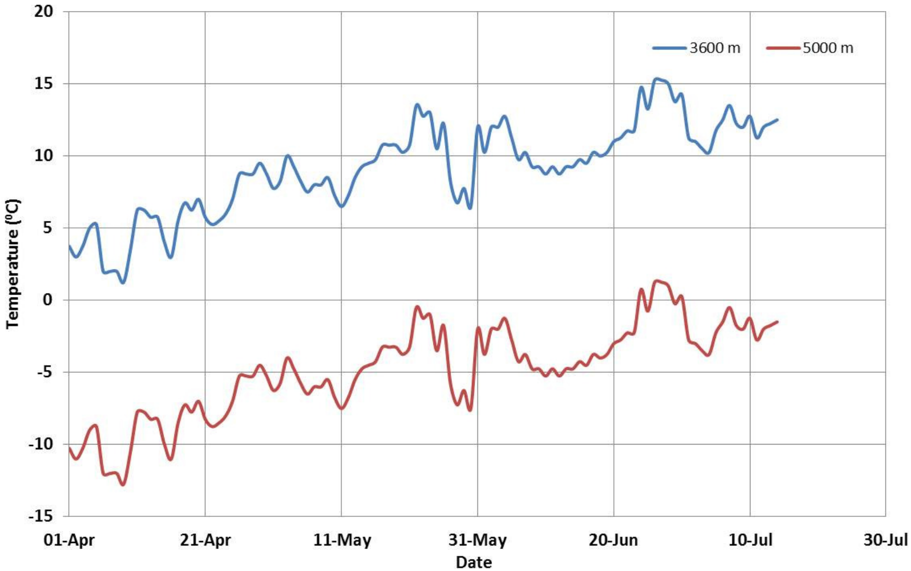

Fig. 10. The daily mean temperature at Kaza at 3600 m in 2009 and the model daily mean temperature at 5000 m altitude. The temperature distribution suggests a substantially lower temperature than melting point between 14 April 2009 and 27 May 2009, suggesting the absence of liquid water during these observations.