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# Influence of shadow on the thermal and optical snow indices and their interrelationship

Retinder Kour, Nilanchal Patel *, Akhouri Pramod Krishna

*Department of Remote Sensing, Birla Institute of Technology Mesra, Ranchi 835215, Jharkhand, India*

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In snow-covered mountainous terrains, topography-induced different illumination conditions would cause varying influence on the snow characteristics in the sunlit and shadowed sites owing to albedo variation. Since the thermal bands suffer less by the shadows as compared to the optical bands, it is imperative to investigate the effect of shadow on the optical and thermal snow indices. The investigation comprises determination of (a) difference of means between the sunlit snow cover and snow cover under shadow for thermal snow indices, optical snow cover indices and optical snow cover characteristic indices and (b) correlation coefficient of the thermal snow indices with the respective optical snow cover indices and optical snow cover characteristic indices. The study was conducted in the test sites of the Chenab basin, western Himalayas using the Landsat-8 Operational Land Imager and Thermal Infrared Sensor data.

The mean values of different snow indices exhibit significant difference between the sunlit and shadow test sites with Z-values ranging between 68.92 and 1220.39 ($p < 0.0001$). Shadow significantly increases correlation of the thermal snow indices with the optical snow cover indices with $r \geq 0.81$, while $r$-values lie below 0.29 in the sunlit test site (Student's $t$-test, $p < 0.0001$). On the other hand, thermal snow indices exhibit low correlation with both optical snow cover characteristic indices in either site; however, shadow induces negative correlation between them ($r = -0.37$ to $-0.62$, $p < 0.0001$). The results ascertain the varying influence of shadow on the optical and thermal snow indices and their interrelationship, which could be significantly helpful for accurate radiative transfer modelling of snow in the light of the seasonal variation in the earth-sun geometry.


## 1. Introduction

Accurate mapping and characterization of snow cover is vital for water management and climate change studies because of its effects on net radiation balance, surface albedo and boundary layer stability (Wang and Tedesco, 2007). It has been reported that depending on the grain size, impurity and age of the snow, freshly fallen snow can reflect up to 80% (Winther et al., 1999; Konig et al., 2001) to 90% (Hall and Martinec, 1985) of the radiation in visible portion of the electromagnetic spectrum. Snow has high heat capacity, thus snow cover insulates the soil surface from the atmosphere and slows down the warming process in spring (Tekeli et al., 2005). Snowfall accounts for a substantial portion of total annual precipitation in many high latitude and mountainous regions (Wang and Tedesco, 2007). Further, reliable estimate of snow cover and snow/ice melt is also necessary for the assessment of glacier mass balance (Huss et al., 2013). Snowmelt runoff serves as a major source of fresh water in many arid and semi-arid regions (Alifu et al., 2015; Kour et al., 2016a).

Over the decades, surge of studies have been conducted with the help of remote sensing data for the delineation of snow and glaciers (Hall et al., 1995; Keshri et al., 2009; Karimi et al., 2015; Kour et al., 2016b), however, the effect of topographic shadows in the mountainous terrain has remained an important issue in this field. In such terrains, topographic shadows may destroy the relationship between the slope gradient and aspect of the surface, the sun position, and reflectance values (Giles, 2001). Several researchers (Giles, 2001; Riano et al., 2003) reported that shadowed areas exhibit reduced values of reflectance as compared to non-shadowed areas with similar surface cover characteristics induced due to topographical variation in the mountainous terrains. Such observations have also been reported for snow cover areas in different parts of the world such as Qilian mountains in China (Xin et al., 2002), central Idaho and southwestern Montana mountains (Crawford et al., 2013) and western Himalayas (Mishra et al., 2010; Singh et al., 2015). Further, topographic shadows may also affect the snowmelt runoff by favouring the snow accumulation for an extended period of time, thus reducing the snowmelt process. In mountainous

* Corresponding author.
*E-mail address:* nilanchal.patel@gmail.com (N. Patel).

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terrain, the proportion of shadow present in a satellite data depends mainly on the topographic relief and sun elevation at the time of image acquisition. Therefore, various techniques such as thresholding (Cheng and Thiel, 1995; Lu, 2006), modelling (Irvin and McKeown, 1989; Koller et al., 1993) and invariant color model (Sarabandi et al., 2004; Arevalo et al., 2008 and references therein) have been implemented for the shadow detection.

Shadowed regions were delineated by applying a threshold on band 3 of Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) data in order to reduce misclassifications among glacier terrain classes (Racoviteanu and Williams, 2012; Shukla and Ali, 2016). Crawford et al. (2013) masked shadowed regions from Landsat imagery by visually identifying dark pixels of shadow, for accurate mapping of snow cover area in mountainous terrain. Heiskanen et al. (2003) reported thermal band thresholding to be an effective means to delineate glacier boundary in cast shadows. On the contrary, Bhambri et al. (2011) observed that shadow areas strongly affect the single thermal band thresholding, which may hamper the automatic mapping of debris-covered glacier areas.

For snow and glacier mapping in undulating terrain conditions, several researchers (Kachouie et al., 2013; Kour et al., 2016c) used thermal bands in addition to optical bands to minimise the effect of topographic shadow. Kachouie et al. (2013) integrated thermal band and normalized difference snow index (NDSI) with the reasoning that thermal bands may be less affected by shadows as compared to optical bands; and developed a new index, termed normalized difference thermal snow index (NDTSI) in order to delineate consistent glacier termini location. More recently, Kour et al. (2016c) developed a new processed thermal snow index, called S3 thermal snow index (S3TSI) that combines thermal band and S3 index, as former is less affected by shadows and latter uses the reflectance characteristics of both snow and vegetation thereby increasing the efficiency of identifying snow cover areas mixed with vegetation (Shimamura et al., 2006). Further, several researchers have reported that normalized difference snow index (NDSI) also has the potential to delineate and map snow even under topographic shadows (Kulkarni et al., 2006; Negi et al., 2010).

NDSI and thermal snow indices may have the potential to delineate snow cover area even under topographic shadows, but shadow may influence the values of various snow indices. Snow indices values are also indicative of several processes, for example, NDSI values increase with snow grain size, moisture and ageing (Negi et al., 2010). Higher values of snow grain size index (SGI) represent larger snow grain size, and higher values of snow contamination index (SCI) represent cleaner snow, whereas SCI remains negative for contaminated snow (Dozier, 1989; Negi et al., 2010). However, these indices values may be affected by the prevalence of shadow, which are widely used for the characterization and automated delineation of snow and glaciers. Kour et al. (2015) investigated the relationship between the snow cover indices and snow cover characteristic indices in both the sunlit and shadowed sites in the Chenab basin, western Himalayas, and observed the prevalence of larger correlation in the shadowed site.

In the light of the above reasoning, the present study was undertaken in the test sites of the Chenab basin, western Himalayas with two main objectives, first to investigate the influence of shadow with respect to sunlit on different thermal snow indices and optical snow cover and snow cover characteristic indices. In essence, we examined the difference in the mean values of snow indices between the test sites of sunlit snow cover area and snow cover area under shadow. Second, to determine the effect of shadow with respect to sunlit on the relationship of thermal snow indices with optical snow cover and snow cover characteristic indices. The investigations performed in the present study are crucial in the context of radiative transfer modelling and glacier topographic characterization in undulating mountainous terrains. Further, the results derived from such investigations could also lead to better understanding of the snow cover characterization in such terrains.

## 2. Study area

The present study was carried out in parts of the Chenab basin, western Himalayas, India (Fig. 1). The Chenab basin is elongated in shape and extends over two states, namely Himachal Pradesh and Jammu and Kashmir. The elevation of the basin varies from 300 to 7103 m above the mean sea level (MSL). The slope is very steep at its source and decreases gradually downstream. The hydropower potential of the Chenab river is very high.

In order to accomplish the objectives envisaged, the present investigation has been performed in the snow cover test sites of two distinct illumination conditions in the study area. The sunlit snow cover test sites, henceforth referred to as the $SCA_{sunlit}$, extend over an area of 34.07 km$^2$ (37,902 pixels), while the $SCA_{shadow}$ represents the snow cover test sites under shadow, covering an area of 12.54 km$^2$ (13,771 pixels).

## 3. Data used and methods

The data used to perform the present investigation include Level 1 T-Terrain corrected Landsat-8 Operational Land Imager (OLI) and Thermal Infrared Sensor (TIRS) data with 30 m spatial resolution (path/row: 148-37, scene ID LC81480372013307LGN00 of November 3, 2013 with scene center time 05:31:45.6314762Z) and 90 m Digital Elevation Model (DEM) of the Shuttle Radar Topography Mission (SRTM) data set. SRTM DEM was selected in view of its higher vertical accuracy as compared to GEODATA DEM-9S and ASTER GDEM (Hirt et al., 2010; Czubski et al., 2013).

The methodology adopted to examine the influence of shadow on the thermal and optical snow indices and the interrelationship between them is presented in the flowchart of Fig. 2. The various tasks performed can be categorised into two categories: the first category comprises pre-processing of the satellite images, surface temperature ($T_s$) retrieval, generation of different snow indices from the processed images and delineation of test sites in sunlit snow cover area and snow cover area under shadow, whereas, the second category involves the different types of analysis pertaining to the determination of influence of shadow on the different snow indices. The analyses comprise computation of mean differences of snow indices between the $SCA_{sunlit}$ and $SCA_{shadow}$, and determination of relationship of thermal snow indices with optical snow cover and snow cover characteristic indices in the respective sites using the $SCA_{sunlit}$ and $SCA_{shadow}$ through Pearson's product-moment correlation coefficient ($r$). The significance of mean difference and correlation coefficient was tested using Z-test and Student's $t$-test respectively.

### 3.1. Image pre-processing

The electromagnetic radiation signals collected by the sensors may be affected by scattering and absorption by aerosols and gases while travelling through the atmosphere from the surface of the earth that will result in incorrect digital numbers (DN values) of the spectral bands. Therefore, it is required to convert the raw DN values to reflectance values by employing atmospheric correction techniques. In the present study, simple dark object subtraction (DOS) method (Teillet, 1986; Chavez, 1996) has been used to perform this task. This involves first the conversion of DN values to at-sensor radiance values using the Eq. (1) (Lu et al., 2002):

$$L_{sat} = [(L_{max} - L_{min})/(Q_{cal\,max} - Q_{cal\,min})](DN) + L_{min} \tag{1}$$

where $L_{sat}$ is the spectral radiance at the sensor, $L_{max}$ is the maximum spectral radiance for a given band, $L_{min}$ is the minimum spectral radiance for a given band, $Q_{cal\max}$ is the maximum quantized calibrated pixel value corresponding to $L_{max}$ and $Q_{cal\min}$ is the minimum quantized calibrated pixel value corresponding to $L_{min}$.