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Empirical relationship between near-IR reflectance of melting seasonal snow and environmental temperature in a Himalayan basin

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Abstract

The snow-melting zone forms a site of marked physical-hydrological processes. A basic requirement for monitoring such zones is the data on temperature distribution, for which the method of environmental lapse rate and remote sensing with thermal infrared scanners have been used earlier. In this study, repetitive multispectral image data sets acquired from IRS-LISS-III satellite sensor have been used for snow mapping in the Gangotri glacier, Himalayas, and topographically corrected reflectance values have been computed using a digital elevation model. Temperature measurements at a field station have been used for estimating temperature distribution in the snow-covered basin on the corresponding dates. It is shown here that in the melting seasonal snow zone, the topographically corrected mean near-IR reflectance systematically decreases from higher to lower elevation levels, and can be broadly related to the environmental temperature distribution in a restricted range of about 0–5 °C. As a large number of satellites routinely provide data in the reflected infrared range, this method appears to have a reasonable potential, at least to provide surrogate data for filling-in gaps in the database, with possible applications in environmental surveillance, runoff modeling, climatic modeling and numerous other snowfield studies.

Keywords: Snow mapping; C-correction; Environmental temperature lapse rate; Himalayas

1. Introduction

Snow and ice cover constitutes one of the most precious natural resources available to mankind. Besides being a source of fresh water, the snow and ice cover affects global and local climate and its behavior is considered to be indicative of climate change. The extent and type of snow cover is important in snow hydrology and snow avalanche studies.

In mountainous terrain such as the Himalayas, snow cover can be of two types: seasonal snow cover and temporary snow cover (Hall & Martinec, 1985). Seasonal snow cover is formed during winter period and gradually disappears during the summer months. On the other hand, temporary snow cover is generated as a result of occasional snow storms during the snowmelt season and may exist for a few hours to a few days. It is the seasonal snow cover that is the dominant source of fresh water in snow-fed streams. Satellite remote sensing observations provide spatial data on snow cover at regular intervals of time and are incorporated in the snowmelt runoff models (SRMs) (Armstrong & Hardman, 1991; Haefner et al., 1997; Hall & Martinec, 1985; Kite, 1991; Martinec et al., 1994; Rango, 1993; Seidel et al., 1994; Singh & Singh, 2001). Temporary snow cover is just local and event dependent and is not discussed any further.

The snow-melting zone forms a site of marked physical-hydrological processes. Its distribution and temperature have a direct bearing on the hydrological behavior of streams and any change in the snowmelt pattern is considered to be indicative of climate change. A basic requirement for monitoring the snow-melting zone is the data on temperature distribution. In mountain hydrology, conventionally, the method of environmental lapse rate has been used to estimate temperatures at

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different elevations (Dunn & Colohan, 1999; Singh & Singh, 2001). Thermal infrared scanners have also been deployed to yield brightness temperatures of snow (Amlien & Solberg, 2003; Key & Haefliger, 1992; Key et al., 1997; Oesch et al., 2002).

In an earlier investigation using IRS-LISS-III multispectral imagery and field meteorological data (Gupta et al., 2005), we have shown that in the melting season (May–September) in the Himalayas, there exists regularly a fringe of lower near-infrared (NIR) reflectance at the lower-outer periphery of the snow cover area. Further, we have related this fringe, both spatially and temporally, with the melting seasonal snow zone deduced from field temperature data.

The purpose of this study is to investigate in detail the spectral characteristics of snow within the melting zone. We report here that the NIR reflectance within the melting snow zone changes with altitude and environmental temperature. This information should be of wider interest to meteorologists, climatologists, hydrologists, environmental scientists and other researchers engaged in snowfield studies.

In order that data obtained from different multispectral satellite sensors is comparable across various topographically varying sites and scene-coverages, it is necessary to rectify the satellite sensor data and obtain topographically corrected reflectance data. This primarily involves use of digital elevation model (DEM) to rectify for effects arising due to variation in illumination geometry and topography, for which a number of methods are available.

In the following paragraphs, first a brief review of the various methods for computing target reflectance is presented. This is followed by a brief description of the study area, data sets and methodology. After this, the strategy of data processing is discussed, which is followed by analysis and interpretation.

2. Computation of target reflectance — A brief review

2.1. Target irradiance

Radiance reaching the sensor depends upon the target reflectance and the solar irradiance on the target. Reflectance (ρ) can be defined as the ratio of the upward flux reflected from the surface to the incoming total flux impinging on to the surface. The effective magnitude of the solar irradiance impinging on a sloping surface is highly dependent on the orientation of the surface in relation to sun. The total solar irradiance on a sloping ground surface is comprised of three components: (a) direct solar irradiance, (b) diffuse irradiance and (c) terrain irradiance. It is given by Eq. (1) (see e.g., Duguay & LeDrew, 1992; Gratton et al., 1993; Sandmeier & Itten, 1997), where,

$E(b, z)$ total irradiance on an inclined surface;
$E^{h}(b, z)$ total irradiance on a horizontal surface;
$E^{h}_{d}(b, z)$ direct component of irradiance on a horizontal surface;
$E^{h}_{f}(b, z)$ diffuse component of irradiance on a horizontal surface;
$k(b, z)$ anisotropy index;
V_d sky-view factor;
V_t terrain-view factor;
ρ_{adj} average reflectance of adjacent objects;
t binary coefficient to control cast shadow;
i local incidence angle; and
θ_z solar zenith angle.

$$\begin{aligned} E(b,z) = {} & t.E^{h}_{d}(b,z).\frac{\cos(i)}{\cos(\theta_z)} \quad (\text{ direct irradiance}) \\ & + E^{h}_{f}(b,z).\left\{k(b,z).\frac{\cos(i)}{\cos(\theta_z)} + (1-k(b,z)).V_d\right\} \\ & \quad (\text{ diffuse irradiance}) \\ & + E^{h}(b,z).V_t.\rho_{adj} \quad (\text{ terrain irradiance}) \end{aligned} \tag{1}$$

The three terms in the above equation correspond to the three components of solar irradiance: direct, diffuse and terrain on the target. The first term on the right corresponds to the direct solar irradiance and makes up the largest amount; however, in shadows, it is absent and there only diffuse and terrain irradiances are present. The diffuse irradiance is largely due to skylight and is a function of the portion of the sky hemisphere not obstructed by topography (sky view factor). The third term, terrain irradiance, takes care of the irradiance arising from the neighboring terrain, i.e. illumination of the target by (cross-) reflections from the adjacent terrain. This is quite important in case of deep valleys particularly when covered with snow. The terrain irradiance depends upon the irradiance of the adjacent terrain, portion of the adjacent terrain seen from the target surface, reflectance of the adjacent terrain and the distance between the adjacent terrain and the sloping target.

2.2. Reflected radiance from the target

From the above, it follows that in an undulating terrain, the reflected radiance reaching the sensor greatly depends upon the orientation of the target (slope and aspect). The Himalayas are characterized by a highly rugged topography with slopes of varying steepness in various directions. In such a terrain, the topography induces a pronounced effect on reflected radiance reaching the sensor. For comparing data from multitemporal coverages, the raw digital numbers (DN values) cannot be used directly since they include effects arising from topography, as well as from sensor calibration, and atmospheric interferences. For this purpose, the raw DN values have to be converted into topographically corrected reflectance image data.

2.3. Reflectance

Reflectance is defined as the ratio of the upward flux reflected from the surface to the total incoming flux impinging on-to the surface. The reflectance properties of materials are highly variable and angle-dependent, and are ideally given by BRDF (bi-directional reflectance distribution function), which conceptually describes reflectance from a surface for all possible angles and directions of incidence combined with all possible angles and directions of exitance (observation). The BRDF is usually unknown and hardly determinable and therefore directional reflectance is generally used.