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Applicability of Landsat 8 data for characterizing glacier facies and supraglacial debris

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ABSTRACT

The present work evaluates the applicability of operational land imager (OLI) and thermal infrared sensor (TIRS) on-board Landsat 8 satellite. We demonstrate an algorithm for automated mapping of glacier facies and supraglacial debris using data collected in blue, near infrared (NIR), short wave infrared (SWIR) and thermal infrared (TIR) bands. The reflectance properties in visible and NIR regions of OLI for various glacier facies are in contrast with those in SWIR region. Based on the premise that different surface types (snow, ice and debris) of a glacier should show distinct thermal regimes, the 'at-satellite brightness temperature' obtained using TIRS was used as a base layer for developing the algorithm. This base layer was enhanced and modified using contrasting reflectance properties of OLI bands. In addition to facies and debris cover characterization, another interesting outcome of this algorithm was extraction of crevasses on the glacier surface which were distinctly visible in output and classified images. The validity of this algorithm was checked using field data along a transect of the glacier acquired during the satellite pass over the study area. With slight scene-dependent threshold adjustments, this work can be replicated for mapping glacier facies and supraglacial debris in any alpine valley glacier.

Introduction

The expression and behavior of a glacier surface is dynamic in temporal domain owing to changing meteorological conditions within a particular mass balance year (Williams et al., 1991). The meteorological parameters which mainly influence these expressions are, the type and amount of precipitation, air temperature and solar insolation, in addition to the presence of supraglacial debris (Shroder et al., 2000). The presence of a thick layer of supraglacial debris towards an ablation zone of glaciers is a part of an efficient sediment transport system (Kirkbride, 1995). Any glacier facies characterization is not complete until the presence of supraglacial debris is also accounted in the characterization. Debris flows, rock-falls, rock avalanches and snow/ice avalanches from adjacent slopes are the main sources of supraglacial debris (Fort, 2000; Hewitt, 2009; Shroder et al., 2000). The observation on the temporal surficial reflectance of a glacier can offer useful inputs to the studies related to glacier dynamics and mass and energy balance. Such observations based on field studies are very time and effort consuming, and costly. The use of satellite data allows some of these changes to be observed and measured with much ease and good accuracy.

Glacier facies, supraglacial debris and their reflectance characteristics

Facies display a unique group of characteristics reflecting the environment under which snow or ice was formed (Hall et al., 1987). Benson (1959) defined, and Muller (1962) modified the concept of glacier facies, which was actually a refinement of latitudinal geophysical classification of glaciers (Ahlmann, 1935). This concept

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Fig. 1. Field photographs of Shaune Garang glacier taken on 18 September 2013: (a) supraglacial debris cover over snout, (b) glacier ice (orange arrow) and terminal moraine (yellow arrows), (c) lateral moraine (orange ellipse) and medial moraine (yellow arrow), (d) medial moraine before slush zone, (e) transverse crevasse (yellow arrow), (f) ice wall at the snout, (g) slush zone (h) snow facies in accumulation zone, (i) Crevasse zone at steep slopes (yellow ellipse) distinguishing slush zone (red ellipse) from snow facies (orange arrow). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

included 'within glacier areal variations' of various surface types (ice, wet snow, dry snow, percolation and slush zones) (Benson and Motyka, 1979; Muller, 1962). Many subsequent research (Paterson, 1981; Williams et al., 1991) modified the concept of glacier facies as per the different kinds of glaciers studied. The areal/volumetric estimates of supraglacial debris improve the studies related to glacier dynamics and mass and energy balance modelling. Studies have shown significant effect of thick debris cover on glaciers to promote the formation of supraglacial lakes (Benn and Warren, 2000; Reynolds, 2000) and in reducing their melting rates, thus causing their delayed response to climate change (Benn and Evans, 1998; Mattson, 2000; Pelto, 2000).

The ablation zone of a glacier is characterized by the exposed ice, while the accumulation area mainly consists of wet snow, percolation and dry snow facies (Winther, 1993). Different facies represent surfaces with relatively different characteristics in terms of reflectance, thereby playing a crucial role in the Earth-atmosphere energy balance (Warren and Wiscombe, 1985). Zeng et al. (1984) discussed the spectral reflectance of various surface types for snow and ice in different formation stages, with reflectance in visible bands in decreasing order: fresh snow > firn > glacier ice > refreezing ice > dirty glacier ice. Snow albedo show inverse relationship with snow grain size (Wiscombe and Warren, 1980) and direct proportionality with solar zenith angle (Liang, 2004). In visible wavelengths, the supraglacial debris cover show lesser reflectance than any of the snow or ice surfaces. But in larger parts of SWIR wavelengths, the debris cover has much higher reflectance.

Uses and limitations of remote sensing for mapping glacier facies and supraglacial debris

Ostrem (1975) used satellite images to establish a temporal straight-line function relationship between in-situ mass balance and equilibrium line altitude (ELA) for a few Norwegian glaciers. Holmgren et al. (1975) and Rango et al. (1975) used Landsat 1 MSS (Multispectral Scanner) band 7 (NIR) for detecting surface water over ice and snow. Crabtree (1976) utilized Landsat MSS imagery to define wet snow line. This, however, was later identified as a wrong interpretation, because the existence of wet snow line depends on wetting of the entire annual unit, and since it is not a surface phenomenon, it cannot be located on Landsat imagery. Williams (1987), at the end of the mass balance year delineated the firn-line for Iceland ice cap by using Landsat imagery and subdivided some of the facies using spectral reflectance. Dozier et al. (1981) discussed capabilities of Landsat TM (Thematic Mapper) SWIR bands for greater sensitivity to snow grain-size, thus having potential for distinguishing boundaries between facies. Hall et al. (1987) proposed TM band ratio (band 4/band 5) for enhancing snow and ice features owing to large differences in the spectral response in the respective bands. Winther (1993) used Landsat TM and in-situ summer reflectance of glaciers in Svalbard for deter-