Remote Sensing of Environment 140 (2014) 165–178

Contents lists available at ScienceDirect

Remote Sensing of Environment

journal homepage: www.elsevier.com/locate/rse

Using atmospherically-corrected Landsat imagery to measure glacier area change in the Cordillera Blanca, Peru from 1987 to 2010☆

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ARTICLE INFO

Article history:
Received 18 September 2012
Received in revised form 25 July 2013
Accepted 18 August 2013
Available online 23 September 2013

Keywords:
Glacier change
Cordillera Blanca
Atmospheric correction
Landsat

ABSTRACT

The dynamic, tropical glaciers of the Peruvian Cordillera Blanca are rapidly changing and these changes are expected to affect water availability, especially during the dry season. In this study, we quantify recent changes to these water reservoirs, providing estimates of glacier area in the Cordillera Blanca and sub-watersheds of the Rio Santa for the following years 1987, 1996, 2004, and 2010. We explore the effects of atmospheric and topographic corrections by comparing debris-free glacier area estimates generated using raw scenes and corrected scenes. Our results suggest that these corrections can have a significant impact on debris-free glacier area estimates when the same threshold is applied. Debris-free glacier area estimates derived from uncorrected scenes are approximately 5% less than debris-free glacier area estimates derived from atmospherically-corrected scenes. We determined that debris-free glacier area estimates are most sensitive to the choice of threshold and topographic effects. To map glacier area change, we used high-resolution satellite imagery to calibrate our selection of a single threshold for the Normalized Difference Snow Index (NDSI). This threshold value was applied to all NDSI images, which were derived from four carefully selected and atmospherically-corrected Landsat Thematic Mapper (TM) scenes acquired at the end of the dry season. In order to calculate total glacier area, we manually mapped debris-covered glaciers, because automated methods were unsuccessful in this region. As of August 2010, the Cordillera Blanca had a total glacier area of 482 km^2, which amounts to a 25% decrease since 1987. Glaciers in the southern portions of the Cordillera Blanca, which have lower median elevations on average, lost a greater percentage of their area from 1987 to 2010, relative to their northern counterparts. Overall, glacier area change in the Cordillera Blanca appears to be accelerating. Between 2004 and 2010, glaciers in the Cordillera Blanca lost area at a rate that was approximately 3.5 times the average rate of area loss from 1970 to 2003.

1. Introduction

Tropical glaciers, like those in the Cordillera Blanca of Peru, are sensitive indicators of climate change (Kaser & Osmaston, 2002) and vital dry season sources for drinking water, agriculture, and hydropower generation (Bradley, Vuille, Diaz, & Vergara, 2006; Mark & McKenzie, 2007). Remote sensing studies focusing on this region have shown that multi-spectral satellites such as Système Pour l'Observation de la Terre (SPOT) (Georges, 2004; Racoviteanu, Arnaud, Williams, & Ordonez, 2008), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) (UGRH, 2010), and Landsat Thematic Mapper (TM) (Mark & Seltzer, 2003; Silverio & Jaquet, 2005) are useful tools for monitoring changes in glacier extent on approximately decadal time scales. Recent studies focusing on hydrologic modeling of glacier contribution to watersheds in the Cordillera Blanca have utilized multi-temporal estimates of glacier area derived from remotely sensed data to describe the effect that glacier change has had and will have on water resources for this region (Condom et al., 2011; Juen, Kaser, & Georges, 2007). Baraer et al. (2012) argue that discharge has already peaked for seven of the nine glacierized watersheds they studied in the Cordillera Blanca. It is crucial that the shrinking water reservoirs of the Cordillera Blanca continue to be monitored both on the ground and remotely, since accurate estimates of glacier area and mass balance are required for calibrating hydrologic models used to make predictions about future runoff under different climate scenarios.

Manual delineation, or hand-digitization, of remotely sensed images had been considered the most accurate method for mapping glaciers (Albert, 2002), but this method is very time-consuming for a multi-temporal change analysis of a large area, such as an entire mountain range. Automated glacier mapping methods using various band ratios have been applied to map glaciers at local to regional scales because these methods are easier to implement, frequently just as precise as manual digitization (Paul et al., 2013), and provide more consistent results. Automated methods for mapping glacier ice utilize different bands of the electromagnetic (EM) spectrum. Debris-free glacier ice is

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http://dx.doi.org/10.1016/j.rse.2013.08.026

highly reflective in the visible part of the EM spectrum (0.4–0.7 μm), less so in the near infrared (0.7–1.0 μm) portions of the EM spectrum, and is nearly zero in the shortwave infrared portion of the EM spectrum. It is this contrast in reflectance that enables automated mapping of debris-free glacier ice. Automated methods that rely on this contrast in reflectance are not effective for mapping debris-covered glaciers because rock debris with a different spectral signature obscures the underlying ice. While it is important that both debris-free and debris-covered ice are mapped accurately to account for total glacier area, the major focus of this paper is mapping changes in debris-free glacier area with automated methods since debris-covered glacier area is estimated to be very small in this region.

Paul, Kääb, and Haeberli (2007) and Paul and Kääb (2005) found that a simple band ratio using Landsat TM bands 3 (0.63–0.69 μm) and band 5 (1.55–1.75 μm) was effective for mapping shadowed ice, but tended to misclassify water bodies as ice. A TM band 1 (0.45–0.52 μm) threshold is often used in conjunction with the TM3/TM5 ratio because it can be used to optimize the classification of ice/rock in cast shadow (Paul & Andreassen, 2009; Paul & Kääb, 2005; Paul et al., 2007). A simple ratio using Landsat TM band 4 (0.76–0.90 μm) and band 5 has also been used effectively for mapping glacier ice (Jacobs, Simms, & Simms, 1997; Paul, Kääb, Maisch, Haeberli, & Kellenberger, 2002), but this method is less effective in deeply-shadowed areas. Racoviteanu et al. (2008) used the Normalized Difference Snow Index (NDSI; Hall, Riggs, & Salomonson, 1995) with SPOT scenes to map glaciers in most of the Cordillera Blanca, showing that the NDSI was effective at distinguishing glacier ice from non-ice areas, especially where the ice is shadowed. The NDSI uses the difference between a visible (TM band 2, 0.52–0.60 μm) and mid-infrared band (TM band 5, 1.55–1.75 μm) divided by the sum of those bands. For debris-free glacier areas, the NDSI is normally highest over fresh snow and lowest over wet and/or dirty ice and shadowed ice.

Most glacier mapping studies utilize raw quantized radiance values, or digital numbers (DNs), measured at the sensor, but when possible, it is preferable to perform atmospheric and topographic corrections so that the analyst may work with data expressed in actual physical units, such as reflectance. These corrections can help to standardize scenes from different dates and/or sensors, but careful scene selection is also very important. Even though most mountain glaciers are at high elevations and, relative to targets near sea level, there is less atmospheric mass between the target and the sensor, optical satellite imagery used in multi-temporal glacier change studies should be atmospherically-corrected to account for atmospheric scattering by gaseous and aerosol constituents. Atmospheric scattering and absorption affect light transmittance through the atmosphere and distort the measured reflectance characteristics of surface materials. Reflectance from the target of interest is modified by atmospheric effects and path radiance, which is additional light measured at the sensor that has not interacted with the target (Vermote, Tanre, Deuze, Herman, & Morcette, 1997). The process of absorption, either by gas molecules or terrain, converts the sun's energy to a different form. Most satellite sensors have already been optimized to record electromagnetic data from atmospheric windows where atmospheric absorption is low. For mountain glaciers, the process of Rayleigh scattering is particularly important because most Rayleigh scattering, commonly by gas molecules like oxygen and nitrogen, takes place between 2 and 8 km in the atmosphere (Jensen, 2005). Atmospheric correction is especially important for mapping methods which utilize bands in the visible spectrum, such as the TM3/TM5 ratio or the NDSI, because atmospheric Rayleigh scattering varies inversely to the fourth power with wavelength (Cracknell & Hayes, 1991). Mie scattering, or aerosol scattering, usually occurs in the lower 4.5 km of the atmosphere while non-selective scattering of water vapor usually takes place in the lower 2 km of the atmosphere.

When possible satellite images used for change analysis in mountainous terrain should also be corrected for topographic effects like slope and aspect, since these effects can introduce additional radiometric distortion, especially in mid-infrared bands (Kawata et al., 1990). There are two general methods for applying a topographic correction: band ratioing and correction based on local illumination geometry. Band ratios have been shown to eliminate, or at least reduce, illumination differences resulting from rugged terrain (Jensen, 2005). However, band ratios utilizing visible spectrum bands which have not been radiometrically- or atmospherically-corrected can be problematic (Crippen, 1988). Corrections based on illumination geometry require an accurate DEM that has the same resolution as the data acquired from the sensor. Gupta, Ghosh, and Haritashya (2007) and Riano, Chuvieco, Salas, and Aguado (2003) summarize some of the most common correction methods based on illumination geometry, such as the Cosine correction (Teillet, Guindon, & Goodenough, 1982), Minnaert correction (Minnaert, 1941), Statistical–empirical correction (Teillet et al., 1982), and C-correction (Teillet et al., 1982). The C-correction method is a statistical method that tends to reduce the over-correction of weakly-illuminated regions. Gupta et al. (2007) and Shukla, Gupta, and Arora (2009) both used the C-correction method to obtain reflectance data normalized for topographic effects in a Himalayan basin. They found that this method was preferable because the Cosine-correction commonly over-corrects weakly illuminated regions (Meyer, Itten, Kellenberger, Sandmeier, & Sandmeier, 1993) where diffuse radiation is significant. Other studies also indicate that the C-correction often performs well (Meyer et al., 1993; Riano et al., 2003).

Two final issues that are sometimes left unaddressed in glacier mapping studies are the selection of a threshold for automated glacier mapping methods and threshold sensitivity. In terms of threshold selection, many analysts report making a visual comparison between glacier extent mapped with a certain threshold and a color- or false-color-composite image from the same scene (Paul & Andreassen, 2009; Racoviteanu, Paul, Raup, Khalsa, & Armstrong, 2009). Others have chosen a threshold based on an inspection of the NDSI image histogram (Silverio & Jaquet, 2005). In this paper, we suggest that, when possible, a threshold choice should be quantitatively and qualitatively validated using either ground data or higher-resolution satellite imagery from approximately the same date. Thresholds can vary from scene to scene or even within a scene, depending on the presence of fresh snow or shadows. Ideally for a change analysis spanning multiple years or decades, the analyst would have selected satellite images from within the same month, preferably towards the end of the melt or dry season to capture minimum glacier extent and exclude seasonal snow. Once spectrally similar scenes are selected, atmospheric and topographic corrections can further facilitate the selection of a single threshold. These corrections essentially standardize scenes from different dates, assuming that other sources of variation, such as smoke, thin clouds, and fresh snow, are not introduced.

In this study, we explore the effects of atmospheric and topographic corrections as well as threshold sensitivity on debris-free glacier area generated using the NDSI. We used atmospherically-corrected Landsat TM imagery and applied a single NDSI glacier threshold to provide a measure of glacier change in the Cordillera Blanca from 1987 to 2010. We examine glacier area change for 11 sub-watersheds of the Rio Santa (Fig. 1). We also estimate the total glacier area change for the entire Cordillera Blanca to fill in data gaps and compare our estimates with previous studies. The specific objectives of this study are to: (1) compare estimates of Cordillera Blanca debris-free glacier area generated from atmospherically- and topographically-corrected satellite imagery and uncorrected imagery; (2) choose a single threshold for mapping debris-free ice in the Cordillera Blanca; (3) to quantify glacier area change from 1987 to 2010 in gauged watersheds draining to the Rio Santa, as well as the entire Cordillera Blanca; and (4) to estimate the uncertainty of our glacier outlines.

2. Study area

The Cordillera Blanca contains the highest concentration of glaciers anywhere in the tropics (Kaser, Ames, & Zamora, 1990). Previous