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Analysis of sub-pixel snow and ice extent over the extratropical Andes using spectral unmixing of historical Landsat imagery

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ABSTRACT

With more than 30 years of imagery, the Landsat database offers potential insights into changes in the global cryosphere. In this study, a Landsat-based sub-pixel fractional snow covered area retrieval model based on spectral unmixing is applied and validated over a southern Andes study region. An application analyzing minimum annual snow/ice covered areas is presented as an example of the utility of the existence of such a model and the Landsat database. The model was validated using high-resolution imagery aggregated to the nominal Landsat resolution, showing good correlation for both fresh snow and ice/old snow presence. Using annual minimum snow/ice retrievals from Landsat 5 and 7, the presence of trends in each snow/ice-covered pixel area was assessed for the 1986–2013 historical period, and three metrics were examined: pixels with significant negative trends, total area loss, and areas with any absolute negative change. Significant negative (area reduction) trends in most of the glacier fronts were found, with a loss of approximately 15% of the original 241 km^2 glacierized/snow area between 1986 and 2011. Trends in fractional values were compared with those derived from traditional binary classification of snow and significant discrepancies were observed. Even though the binary classification identified a greater total areal loss (33 vs. 23 km^2) when comparing scenes from the beginning and the end of the study period, the fractional algorithm identified a larger number of pixels with significant negative trends between 1986 and 2013 (42.3 vs. 10.5 km^2). The binary algorithm resulted in consistent overestimations of ice and snow area and does not offer the ability for identifying subpixel changes. The method could enable future monitoring of Andean and other glaciers and snow cover at a sub-pixel scale over large scales, and with Landsat 8 in orbit a continuous stream of more than 30 years of data is already available.

1. Introduction & background

Snow and ice melt runoff from mountainous regions is one of the most important sources of water for many areas around the world, including significant portions of the Andes (Barnett, Adam, & Lettenmaier, 2005; Vergara et al., 2007). Water availability during spring or summer seasons is strongly dependent on the Snow Water Equivalent (SWE) contained in seasonal snowpacks (Masiokas, Villalba, Luckman, Le Quesne, & Aravena, 2006) and also in glaciers which supply runoff when the snowcap is completely depleted. Despite this, there are still significant limitations involving measurement of variables such as snow depth, glacier volume and glacier extent, particularly in developing countries, due to factors such as inaccessible topography or high logistical costs, which reduce the ability of water agencies to directly assess snowpack characteristics. This is particularly true over the Andes where the topography varies abruptly from sea level to over 6000 m within a 50-kilometer span, and there is a shortage of historical snow measurements.

Glaciers and ice-bodies are important to analyze given their contribution to the water supply during the late summer season (Vergara et al., 2007; Bown, Rivera, & Acuña, 2008; Ohlanders, Rodriguez, & McPhee, 2013). Oerlemans (1994, 2005) found significant glacial retreat throughout the world during the last 50 years, and findings over the Andes are consistent with this signal. Nicholson et al. (2010) analyzed glaciers over the South American latitudinal band of 28°S–30°S, and found negative areal changes for most of the glaciers during the latter 50 years of the 20th century, suggesting that the majority of them will disappear towards the end of the 21st century according to climate projections. Rivera, Bown, Acuña, and Ordenes (2008) also showed recent negative changes in glacier extent for a large section of the Chilean Andes (18°S–54°S) using a set of remote sensing images and historical aerial photography. For the Southern Patagonian Region, Rignot, Rivera, and Casassa (2003) showed that the melting ice from Patagonia Icefields during the 1995–2000 years have contributed to more than 0.1 mm of annual sea level rise. Similarly, Glasser, Harrison, Jansson, Anderson, and Cowley (2011) show that since the Little Ice Age the Northern and Southern Patagonia Icefields have contributed to approximately 0.0018 and 0.0034 mm per year of sea level rise. Finally, Davies and Glasser (2012) used trimlines and moraines to identify changes in the aforementioned icefields and the Darwin Cordillera (southern

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Patagonia), finding a glacier area reduction of 15.4% in the three study sites. Masiokas et al. (2009) studied glacier fluctuations during the past 1000 years over the southern Andes region using a combination of paleoclimatological techniques and modern remote sensing systems, finding significant declines in most of the studied glaciers during the last century. Barnett et al. (2005) related changes in glaciers to significant decreases in dry-season water supply, and suggested that the disappearance of these ice bodies will have significant impact on regional water usage.

Among the possible tools that could enhance knowledge of snow and glacier processes over these types of regions are remote sensing products, particularly those derived from satellite imagery. These products are not limited as much by logistics as in-situ measurements are and usually have global coverage. For snow and ice, several tools have been developed that help to directly or indirectly estimate the presence and volume of snow over mountainous regions. The NASA MODIS (Moderate Resolution Imaging Spectroradiometer) product suite (Hall, Riggs, Salomonson, DiGirolamo, & Bayr, 2002) has been used for snow covered area estimation and applied to several hydrological analyses, including snowmelt modeling (Tekeli, Akyürek, Arda Şorman, Şensoy, & Ünal Şorman, 2005), hydrologic modeling (Parajka & Blöschl, 2008; Powell, Blesius, Davis, & Schuetzenmeister, 2011; Ragettli, Cortés, McPhee, & Pellicciotti, 2013) and glacier monitoring (König et al., 2001; Lopez, Sirguey, Arnaud, Pouyaud, & Chevallier, 2008). However, the original MODIS suite of products has retrieval issues such as failing to detect snow presence in the higher elevations at the end of the ablation season, which can result in biases (Rittger, Painter, & Dozier, 2013) or underestimation of the actual snow covered areas due to the use of a binary classification of each pixel instead of more precise fractional estimates. The more recently developed fractional MODIS snow cover product (MOD10A1), which retrieves subpixel fractional Snow Covered Area (fSCA), was developed based on regression with Landsat Thematic Mapper Normalized Difference Snow Index (NDSI, Salomonson & Appel, 2004) and offers a much more accurate approach for fSCA retrieval. Arsenault, Houser, and De Lannoy (2012) performed an evaluation of MOD10A1 in terms of the capacity of snow presence detection using snow stations in Colorado and Washington, finding limitations due to viewing angles and artifacts inherent to the sensor itself. However, despite the limitations, they showed improvement of snowpack model results when using the product in a direct insertion data assimilation approach. According to the results of Rittger et al. (2013) there is still significant snow covered area missed by the algorithm in comparison to more advanced spectral unmixing products, however MOD10A1 shows an increased value over the original MODIS binary snow covered product, reinforcing the need for developing fractional algorithms.

One example of a spectral unmixing product is MODSCAG (MODis Snow Covered Area and Grain size, Painter et al., 2009), which was developed to directly estimate the constituent fractions of each pixel instead of relying in index-based or binary approaches, resulting in fractional areal estimates of snow cover, vegetation and bare soil/rock cover. The algorithm was validated using an analogue spectral mixing algorithm using Landsat Thematic Mapper data (Painter et al., 2009) over the Sierra Nevada, California, and according to the results of Rittger et al. (2013) the model had a superior performance in comparison to previous MODIS-based binary and fractional products. The MODSCAG product (and MODIS in general) is somewhat limited by the raw MODIS data resolution (500 m) and off-nadir viewing angle in many images, both of which exacerbate errors when there is significant forest cover (Xin et al., 2012).

Another relevant data stream is the Landsat based family of sensors, particularly Landsat 5, 7 and 8 with the Thematic Mapper, Enhanced Thematic Mapper and Operational Land Imager. These sensors have a nominal 30-meter resolution, with a combined global coverage from 1984 until present day. Landsat-based sensors are nadir looking and thus less limited when facing rugged topography or heavily forested sites. Several authors have used Landsat imagery for studying the evolution of glacierized areas and for fSCA retrieval. In particular, Rosenthal and Dozier (1996) devised an automatic mapping method for sub-pixel snow cover using a spectral unmixing model combined with regression trees. Their method was validated for the Sierra Nevada in California, showing an error of approximately 7% in their estimates when validated against high-resolution aerial images. Bown et al. (2008) used single scenes of Landsat TM and ETM+ imagery, combined with ASTER (Advanced Spaceborne Thermal Emission and Reflection), Shuttle Radar Topography Mission elevation values and photographic data to manually identify changes in glacier area over the Central Chilean Andes during the second half of the twentieth century, and in line with aforementioned studies they obtained negative changes. Espizua and Maldonado (2007) used the same sensors' images together with the binary classification of Dozier (1989) to identify glacier extent and their temporal evolution over a similar region during the 20th century. Hanshaw and Bookhagen (2013) used ASTER, TM and ETM+ images to analyze glacier area, lake area and snowline evolution using an index based approach along with a spectral unmixing model (Roberts et al., 1998) during 1972 to 2012 over tropical Peruvian glaciers. Burns and Nolin (2014) use a binary methodology to analyze glaciers over the Cordillera Blanca (Perú), finding decreases in area in the order of 25% for the 1987–2010 period. In a similar fashion, several other authors have used single Landsat TM images for identification of glacial coverage extent (e.g. Bolch, Menounos, & Wheate, 2010; Hall, Foster, Chien, & Riggs, 1995; Silverio & Jaquet, 2005).

In this paper an automatic fractional Snow Covered Area retrieval model based on the spectral unmixing methodology presented by Painter, Dozier, Roberts, Davis, and Green (2003) (with some modifications) is applied to the Landsat TM and ETM+ sensors. To the author's knowledge, the use of Landsat over the Chilean–Argentinean Andes has been limited until now to single scene visual comparative analysis or glacier inventory (e.g., Casassa et al., 2002; Davies & Glasser, 2012; Masiokas et al., 2009; Rivera, Acuna, Casassa, & Bown, 2002) and to analysis based on binary identification (e.g. Burns & Nolin, 2014), no operational automated unmixing model designed especially for Landsat has been applied to retrieve fractional snow covered area estimates over the region. The main objective of this paper is to present and validate a spectral unmixing model for snow cover over the Andes based on Landsat imagery that could serve as a standard methodology for long term monitoring of snow and glacier covered areas. The use of Landsat instead of previously applied MODIS imagery (Cornwell, 2012; Martínez, 2010) would provide a significant leap forward in terms of resolution (30 m vs. 500 m) and hence better characterization of snow cover heterogeneity due to topography and other factors that are possibly overlooked due to the large pixel size of MODIS. For example, annual glacier retreat or variability in many cases is in the order of dozens of meters, and thus such change would be difficult to identify using the MODIS sensor resolution. Emphasis was taken during the validation step in order to evaluate model performance, robustness under different combinations of solar zenith angle and sensor saturation to ensure that unbiased fSCA estimates were obtained. Following model development and validation, the following research questions are proposed for an example of model application over a highly glacierized test sub-region:

- How do trend estimates derived from fractional algorithms differ from those derived from binary classification?
- What is the extent of the change over the particular region analyzed?

In Section 2 of this paper the satellite data that is used for this analysis is presented along with the spectral unmixing algorithm and the methodology for trend testing. In Section 3 the validation and trend testing results and analysis are presented, and finally Section 4 presents the conclusions derived from the analysis performed.