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Towards an enhanced method to map snow cover areas and derive snow-water equivalent in Lebanon

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SUMMARY

Snow cover contributes to the definition of the hydrologic system of most River Basins in Lebanon. Despite its importance little is known about the proper quantification of snow cover extent and snow water equivalent (SWE), as well as the snow contribution to the hydrologic budget at the national scale. By taking advantage of the moderate-resolution optical sensors (MODIS) from both Terra and Aqua satellites it was possible to generate enhanced, eight-days, Terra-Aqua Combined (TAC) product set at a spatial resolution of 500 m. An innovative method that combines the AMSR-E SWE data (∼25 km spatial resolution) and the enhanced TAC dataset was developed to derive a SWE product at a sub-pixel spatial resolution of 500 m. Both the enhanced TAC and the downscaled SWE were developed for the entire Lebanon. The enhanced TAC dataset was found to reduce cloud cover area by ∼13% when compared to the original MOD10A2 dataset. Snow cover area was validated against ETM+ data and the SWE was assessed against in situ measurements; the overall accuracy of the snow cover maps was ∼85%, whereas, the comparison between ground points measured and remotely sensed derived SWE indicates a poor correlation. This study concluded that while the use of TAC is well suited for the assessment of snow cover extent nationwide, the derived SWE from AMSR-E is not fully deployable in Lebanon. Meanwhile, a snow melt method that takes advantage from the remotely sensed SWE is needed to better achieve results suitable for hydrologic studies.

1. Introduction

The Lebanese mountains chains (i.e. Mount and the Anti-Lebanon) play a unique role in the distribution of rainfall and snow and eventually controlling the hydrologic behaviors of most river systems. The country's climate is characterized by the prevailing Mediterranean in the coastal and mountain areas and semi-arid to arid in the inland areas. The climate system and the topography of the country results in high differences and seasonal variability of precipitation and temperature. Precipitation ranges from 300 mm/year in the inland arid areas to more than 1200 mm/year over Mount Lebanon. Snow is more frequent at altitudes higher than 1200 m and has an estimated annual snowpack volume between 1200 and 2000 MCM/year (∼30% to 40% of the annual precipitation) (Shaban et al., 2004; Aouad Rizk et al., 2005).

Snowmelt which usually occurs during spring, at the time where there is little contribution from rainfall, has great influence on the observed spring and river discharges. Despite their impact on the hydrologic regimes of most rivers, little is known about the snowpack dynamics in Lebanon. Same applies to snow accumulation and melting.

Remote sensing technology provides a mean to acquire information on the spatial distribution and thickness of snow cover at a relatively low cost. Satellite remote sensing primary data products used in this study are the snow cover area (SCA) and the snow water equivalent (SWE). Optical sensors are being used to derive accurate SCA and snow extent estimates at higher spatial resolution. The advantage of these sensors is attributed to the fact that snow contrasts greatly with its surroundings due to its high albedo (Gafurov and Bardossy, 2009). Despite their advantage, optical sensors such as MODIS and SPOT observations are limited to day time and are usually subject to cloud cover. Both snow cover area and snow extent lack the information about snow depth or water volume contained in the snowpack. In contrast to the optical sensors, passive microwave satellite remote sensors are known to provide snow thickness where there is no access to in situ snow depth measurements (Foster et al., 2005; Gao et al., 2010). These sensors are well known to provide SWE estimates, at regional scale, due to the coarser resolution offered (Clifford, 2010).

Previous researches suggest that remotely sensed SCA, snow extent, and SWE can enhance our understanding of snowpack

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distribution and improve the quantification of available water resources in remote areas (Yang et al., 2009). SCA has been successfully used in many studies to model snowmelt at the basin scale (Immerzeel et al., 2009; Powel et al., 2011; Gurung et al., 2011). The successful use of passive microwave SWE is usually subject to the study area topography and roughness and the snowpack depth (Andreadis and Lettenmaier, 2006).

Many literatures addressed the limitation found in the remotely derived SCA and SWE data products. Main focus areas, in the optical domain, concentrated on finding new algorithm to enhance the accuracy of snow products. For instance, Sirguey et al. (2009) developed a new methodology for the monitoring of the snow cover from MODIS NDSI data. Ault et al. (2006) and Gao et al. (2010) investigated new methods to enhance the accuracy of the MODIS data by minimizing cloud contamination. The combination between the two MODIS products Terra and Aqua was found to be useful in decreasing cloud effects (Xie et al., 2009). Studies in the microwave domain focused on finding new ways to improve SWE derived from the AMSR-E sensor using ground SWE measurements (Derksen, 2008; Langlois et al., 2008). Other studies focused on comparing and/or combining data from the AMSR-E with data from other sensors such as the SSM/I (Pulliainen, 2006; Vuyovich and Jacobs, 2011).

In order to better enhance the spatial resolution of SWE, different studies focused on integrating the optical and passive microwave sensors (Liang et al., 2008; Gao et al., 2010). Gao et al. (2010) used an enhanced method in order to derive cloud-free snow cover from the Terra-Aqua MODIS data and then developed a methodology in order to derive sub-pixel SWE data from the combined AMSR-E and MODIS systems.

This paper focuses on applying an algorithm for combining the Terra-Aqua MODIS data products into a single TAC (i.e. Terra-Aqua Combined) dataset. The development of TAC relies on methodologies such as the one used by Liang et al. (2008) and Gao et al. (2010). The new TAC product is validated against snow data product derived from Landsat ETM+. A new algorithm is developed in order to downscale the AMSR-E data using the MODIS newly derived TAC dataset. In contrast to the approach developed by Gao et al. (2010) where the AMSR-E data were equally distributed over the MODIS data, the proposed methodology accounts for statistical distribution of snow using a weighting factor based on the number of snow day(s) per year. This combination is sought to provide an enhanced dataset for Lebanon by combining snow cover area, snow extent, and SWE at a downscaled spatial resolution of 500 m. In situ measurements for snow depth and density are used in order to evaluate the accuracy of the sub-pixel derived SWE.

2. Study area

Lebanon, with an area of about 10,400 km^2, receives between 800 and 1500 mm of precipitation each year. The climate variability is highly influenced by the orographic effect of the country's topography and the prevailing Mediterranean climate which limits precipitation to the winter season. Lebanon is divided into four distinct physiographic regions – the coastal zone, the Mount Lebanon, the Bekaa Plain and the Anti-Lebanon. Fig. 1 illustrates the country's topography were the gradual increase in altitude is known to produce colder winters, increased precipitation and snow fall (UNEP, 2007). Snow cover remains for more than four months on mountain crests. Around 25% of the country's total area is covered by snow each year (Shaban et al., 2004). The snow cover area contributes to the feeding of 15 main river basin systems and more than 2000 springs. Snow also contributes to groundwater recharge via a number of aquiferous formations and karstic galleries (Shaban, 2010).

3. Datasets

Four data sets are used in this study. (i) The eight-day MODIS snow products of MOD10A2 (Terra) and MYD10A2 (Aqua) at a spatial resolution of 500 m are used to extract cloud free TAC product; (ii) the Enhanced Landsat Thematic Mapper-plus (ETM+) data with 30 m spatial resolution is used to validate the TAC algorithm; (iii) the AMSR-E/Aqua 5-day L3 SWE at 25 km spatial resolution is used to extract SWE and the combined MODIS and AMSR-E data are used to generate the SWE at sub-pixel scale; and (iv) in situ snow data are used to validate the SWE values.

3.1. MODIS snow cover products

The MODIS sensor is operational onboard two Earth Observation System (EOS) satellites, Terra and Aqua. The MODIS snow and ice products are being derived and provided through the Distributed Active Archive Center (DAAC) of the National Snow and Ice Data Center (NSIDC) since September 2000 for Terra and July 2002 for Aqua. The MOD10A2 and MYD10A2 8-Day L3 snow cover data consist of 1200 km by 1200 km tiles at a spatial resolution of 500 m gridded using a sinusoidal map projection. Data sets contain a data fields for maximum snow cover extent over an eight-day compositing period and a chronology of snow occurrence observations in compressed Hierarchical Data Format-Earth Observing System (HDF-EOS) format. The MODIS snow cover data for both sensors is based on a snow mapping algorithm that make use of the Normalized Difference Snow Index (NDSI) (Hall and Salomonso, 2004). MODIS snow cover images are coded raster. The maximum snow extent coded integer values include: 0 (missing data), 1 (no decision), 11 (night), 25 (land – no snow detected), 37 (lakes – inland water), 39 (ocean), 50 (cloud), 100 (lake ice), 200 (snow), 254 (saturated MODIS sensor detector), and 255 (fill – no data expected for pixel) (Hall and Salomonso, 2004).

3.2. AMSR-E SWE products

The AMSR-E instrument is a multi-frequency, dual-polarized passive microwave radiometer launched on onboard the NASA Earth Observing System (EOS) Aqua satellite in May 2002. AMSR-E provides global measurements of terrestrial, oceanic, and atmospheric variables for the investigation of water and energy cycles. The algorithms for the retrieval of SWE have been developed and improved by Tong and Velicogna (2010) and are based on the brightness temperature (Tb) difference between channels due to the attenuation of snow on the microwave radiation from the snow and underlying ground. The AMSR-E/Aqua 5-day L3 Global SWE EASE-Grid data were downloaded from the National Snow and Ice Data Center (NSIDC) in Boulder, Colorado (ftp://sidads.colorado.edu/pub/DATASETS/brightness-temperatures/polar-stereo/tools/). These Level-3 snow water equivalent (SWE) data sets contain SWE data and quality assurance flags mapped at 25 km Equal-Area Scalable Earth Grids (EASE-Grids) and covers the time period between June 2002 and October 2011. Data are stored in Hierarchical Data Format – Earth Observing System (HDF-EOS) format. The pixel values for SWE include: 0–240 (SWE values divided by 2 in (mm)), 247 (incorrect spacecraft altitude), 248 (off-earth), 252 (land or snow impossible), 253 (ice sheet), 254 (water), and 255 (missing data) (Tedesco et al., 2004).

3.3. Landsat ETM+ satellite data

Eighteen multispectral images were acquired from the Enhanced Landsat Thematic Mapper-plus (ETM+) instrument, avail-