Int J Appl Earth Obs Geoinformation 74 (2019) 222–230

Contents lists available at ScienceDirect

Int J Appl Earth Obs Geoinformation

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

# A method for monthly mapping of wet and dry snow using Sentinel-1 and MODIS: Application to a Himalayan river basin

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ARTICLE INFO

*Keywords:*
Snow
MODIS
Sentinel-1
Google Earth Engine
Himalayas

ABSTRACT

Satellite Remote Sensing, with both optical and SAR instruments, can provide distributed observations of snow cover over extended and inaccessible areas. Both instruments are complementary, but there have been limited attempts at combining their measurements. We describe a novel approach to produce monthly maps of dry and wet snow areas through application of data fusion techniques to MODIS fractional snow cover and Sentinel-1 wet snow mask, facilitated by Google Earth Engine. The method is demonstrated in a 55,000 $km^2$ river basin in the Indian Himalayan region over a period of ~2.5 years, although it can be applied to any areas of the world where Sentinel-1 data are routinely available. The typical underestimation of wet snow area by SAR is corrected using a digital elevation model to estimate the average melting altitude. We also present an empirical model to derive the fractional cover of wet snow from Sentinel-1. Finally, we demonstrate that Sentinel-1 effectively complements MODIS as it highlights a snowmelt phase which occurs with a decrease in snow depth but no/little decrease in snowpack area. Further developments are now needed to incorporate these high resolution observations of snow areas as inputs to hydrological models for better runoff analysis and improved management of water resources and flood risk.

## 1. Introduction

Snow is a key environmental indicator affecting both local and global climate, and is a precious source of freshwater as about one-sixth of the world's population relies on rivers fed by the melting of seasonal snow and glaciers (ESA, 2015). The Himalayas are of particular importance as they hold the third largest deposit of ice and snow in the world, after the polar regions, and are the source of the major rivers of South Asia (Immerzeel et al., 2010). The seasonal snow cover area (SCA) is commonly used as a proxy for estimating and forecasting water runoff from snow melt (Singh and Jain, 2002; Jain et al., 2010a). Previous studies have shown that satellite Remote Sensing (RS) with both optical and Synthetic Aperture Radar (SAR) instruments can inform the understanding of the spatial and temporal variability of SCA (Nolin, 2010). Optical instruments like the Moderate Resolution Imaging Spectroradiometer (MODIS) and the Advanced Very High Resolution Radiometer (AVHRR) provide mature measurements of fractional SCA via the Normalized-Difference Snow Index (NDSI) (Hall et al., 2002). In particular, AVHRR and MODIS offer long time series (from 1978 to today) of SCA measurements which are desirable to monitor long-term hydrological processes (Hori et al., 2017). These measurements refer to the total SCA but cannot discriminate wet and dry snow. Dry snow is only composed of ice particles and air, while wet snow has liquid water as a third component (Rees, 2005). In contrast, SAR can identify areas of wet snow but is unable to detect dry snow (Nagler et al., 2016; Schellenberger et al., 2012; Nagler and Rott, 2000; Baghdadi et al., 1997). Wet snow is typically identified using change detection applied to the backscatter ratio between an image with wet snow and a reference image with only dry snow or no snow. A constant threshold of −2 dB or −3 dB is often used to generate a wet snow mask (Nagler et al., 2016; Nagler and Rott, 2000; Thakur et al., 2013; Stettner et al., 2018). Soft thresholds, as a function of the backscatter ratio, have been used to derive the probability of wet snow (Malnes and Guneriussen, 2002; Longepe et al., 2009; Rondeau-Genesse et al., 2016). Koskinen et al. (1997) also suggested a method to retrieve the fractional cover of wet snow, $F_w$, using the ratio,

$$F_w = \frac{\sigma^0 - \sigma^0_g}{\sigma^0_w - \sigma^0_g} \quad (1)$$

where $\sigma^0$ is the observed backscattering coefficient for an image during the melting period, $\sigma^0_g$ is the backscattering coefficient of snow-free

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https://doi.org/10.1016/j.jag.2018.09.011
Received 12 June 2018; Received in revised form 14 September 2018; Accepted 17 September 2018

ground, and $\sigma_w^0$ is the wet snow backscattering coefficient at the beginning of the melting season. These studies often use optical measurements of SCA to validate the SAR detection of wet snow (with the underlying assumption that all the SCA is wet snow) and have reported that SAR tends to underestimate the SCA near the snow line.

Snowmelt does not necessarily translate into a decrease in total SCA, especially in areas with deep snowpack where melting may result only in a decrease in snow depth. While this melting phase cannot be detected by the MODIS measurements of total SCA alone, it may be detected by the SAR measurements of wet snow. Therefore, combining optical and SAR measurements could improve the monitoring of snowmelt for more accurate runoff estimation and watershed management especially in Sparsely-monitored and inaccessible areas (Rondeau-Genesse et al., 2016). However, so far, the SAR measurements have mainly been used in cloudy conditions to complement the MODIS measurements (Pettinato et al., 2009; Nagler et al., 2008; Solberg et al., 2005). Only Rondeau-Genesse et al. (2016) overlaid wet-snow data from Radarsat-2 and Sentinel-1 over an SCA map from MODIS, so as to derived maps of both wet and dry SCAs for each SAR acquisition date. Yet their study area was limited to a relatively small river basin (14,000 km$^2$) which could be covered by a single RADARSAT-2 ScanSAR Wide image. For larger areas, a strategy is needed to deal with the different imaging dates of multiple SAR swaths. In this paper, we present a strategy based on the fusion of monthly MODIS and Sentinel-1 image composites which allows generating high-resolution monthly maps of wet and dry SCAs over large areas. Our approach also corrects the typical underestimation of the wet SCA by Sentinel-1 using the MODIS measurements and a Digital Elevation Model (DEM). The implementation is facilitated by Google Earth Engine (GEE), a cloud computing platform which provides global-scale analysis capability and a multi-petabyte catalogue of satellite imagery including images from MODIS and Sentinel-1 (Gorelick et al., 2017). The method is applied to a large Himalayan river basin, but could be extended to any area of the world where Sentinel-1 data are routinely available, toward global wet/dry snow maps.

The study presented here is part of the project *Sustaining Himalayan Water Resources in a Changing Climate* (SusHi-Wat), which aims at improving our understanding on how water is stored in, and moves through, a Himalayan river system in northern India.

## 2. Materials

### 2.1. Study area

The study area are the catchments of two large reservoirs in the Indian state of Himachal Pradesh, which have a total catchment area of around 55,000 km$^2$ extending into China. Fig. 1 shows the extent of the whole catchment. The altitude, computed using the DEM from the Shuttle Radar Topography Mission (SRTM), ranges from 600 m above sea level in the west to 6800 m in the Himalayan mountains, and the dominant land covers, according to the MODIS land cover product (MCD12Q1), are sparsely vegetated (41%) and grasslands (26%). Rice and wheat are the main cultivated crops and are grown during the wet season (May–October) and during winter respectively (Kaushik et al., 2011). The area is imaged by 21 Sentinel-1 frames (10 frames from ascending passes, 11 frames from descending passes) and two MODIS tiles (h24v05 and h25v05). The Pong and Bhakra reservoirs are used for hydropower generation and irrigation supply, and are fed by the Beas and Sutlej rivers, respectively. The reservoir inflows are highly seasonal due to the changing importance of snowmelt, with the lowest flows in the winter when precipitation occurs mostly as snowfall. Warmer spring temperatures lead to increasing snowmelt and river flows. As the seasonal snowpack becomes depleted over the summer, glacier melt increasingly contributes to runoff and overlaps in time with monsoon rainfall, leading to the highest river discharges in July–August. On average, these rivers receive between 39 and 60% of their runoff from melting of snow and glaciers (Singh and Jain, 2002; Jain et al., 2010a).

### 2.2. SAR measurements – Sentinel-1

The processing of the images from the Sentinel-1 constellation (Sentinel-1A and Sentinel-1B) was facilitated by GEE which provides a database of analysis-ready Sentinel-1 images. These analysis-ready images were obtained by processing Ground Range Detected (GRD) Sentinel-1 images using the Sentinel-1 Toolbox ESA (2018) to generate calibrated and terrain-corrected images. For the study area and the study period, the standard acquisition mode is single polarization with vertical transmission and vertical reception (VV). Fig. 2 shows that when only Sentinel-1A was available, there were on average a total of 25 images per month, i.e. each image frame was visited about 1.2 times a month, and this number doubled with the addition of Sentinel-1B. It follows that each point of the catchment is visited from 1 to 8 times per month depending on (i) the overlap between the image frames (Fig. 1) and (ii) the acquisition plan of Sentinel-1. June and July 2016 have the lowest numbers of images — 31% and 10% of the study area was not imaged in June and July 2016 respectively. While MODIS is an always-on instrument with daily near-global coverage which provides SCA measurements twice a day (MODIS Terra and MODIS Aqua) for the two swaths needed to cover the catchment, Sentinel-1 needs multiple days to image the whole catchment. This is because (i) the higher resolution of Sentinel-1 (20 m) comes with a smaller image swath (250 km) and (ii) Sentinel-1 only image areas according to its acquisition plan, i.e. the instrument is not always switched on. For example, it took from the 1st May 2015 to the 20th May 2015 (20 days) for Sentinel-1 to image the whole catchment. Therefore, a temporal resolution of one month was deemed appropriate to produce snow maps with full coverage of the catchment (with the exception of June and July 2016).

The low revisit frequency of Sentinel-1, compared to the daily images from MODIS Terra & Aqua, also means that Sentinel-1 may not always fully capture the wet SCA of a given month. The local time of image acquisition is also relevant. Sentinel-1 may miss some wet-snow areas because the images are acquired at around 06:30 (descending pass) and 18:30 (ascending pass) local time, compared to 11:00 and 14:00 for MODIS Terra and MODIS Aqua, respectively. We implemented a method, detailed in Section 3.2, to correct area estimates for the associated potential underestimation of wet SCA by Sentinel-1.

### 2.3. Optical measurements – MODIS

The two MODIS instruments, on-board the National Aeronautics and Space Administration's Terra and Aqua satellites, provide daily images of fractional SCA (no distinction between wet and dry snow) at 500 m resolution (MOD10A1 and MYD10A1 collection 6 products) (Hall et al., 2006). The measurement accuracy is about 93% and varies with the land cover (Hall and Riggs, 2007). The product tends to underestimate snow for forested areas where dense canopies may hide the underlying snow pack. This limitation is not critical for our river basin which has only 1% of forested area. The product may also overestimate snow due to snow/cloud confusion particularly for cloud-shadowed land and thin snow cover. Although methods have been suggested to reduce this overestimation using meteorological measurements from weather stations (Dong and Menzel, 2016a,b), none was implemented in this study as the required meteorological data were not available. Finally the typical image obstruction by clouds was effectively mitigated by generating monthly cloud-free composites — the daily Terra and Aqua images were combined by averaging the cloud-free pixels. On average, from January 2015 to July 2017, each pixel was imaged without cloud 35 times a month, the worst month being January 2017 with, on average, each pixel imaged without cloud only 20 times. Therefore, the monthly composites are expected to reliably capture the average fractional snow cover of each month.