Remote Sensing of Environment 216 (2018) 635–646

Contents lists available at ScienceDirect

Remote Sensing of Environment

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

Daily estimates of Landsat fractional snow cover driven by MODIS and dynamic time-warping

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ARTICLE INFO

Keywords:
Snow cover
Snow accumulation and ablation
Landsat MODIS data fusion
Algorithm development
Time-lapse photography
Time series

ABSTRACT

Understanding seasonal snow cover dynamics is critical for management of hydrological regimes, habitat availability for wildlife species, forest fire risk assessment and recreational demands. Although data products provided at 500 m spatial resolution by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor provide important and readily available information on snow cover, capturing snow dynamics at finer spatial resolutions remains problematic due to the lack of high temporal and spatial resolution data, which limits the number of available observations each year. In this paper we present a new approach to create a daily time-series of 30-m snow observations (called SNOWARP), derived from daily MODIS Normalised Difference Snow Index (NDSI) snow cover data to capture the temporal dynamics of snow cover and Dynamic Time Warping (DTW) to re-order historical Landsat Thematic Mapper (TM), Enhanced Thematic Mapper Plus (ETM+), and Operational Land Imager (OLI) observations to account for inter-annual variability. The SNOWARP product was produced for 2000–2018 for an area of Western Alberta (approximately 30,000 km^2) and was calibrated against a network of time-lapse cameras and snow pillows. Results indicate the RMSE of the SNOWARP fractional product ranges from 31.3%–68.3%, while F score of the SNOWARP binary product ranges from 87.7% - 98.6% when compared to ground truth data. Capturing fractional snow cover at a fine spatial and temporal scale is important due to the spatial heterogeneity of snow cover, particularly in mountainous regions with implications for biodiversity assessment and monitoring. SNOWARP demonstrates a novel method to increasing the temporal resolution of Landsat-derived snow cover data, providing valuable insights on regional snow cover dynamics for use in a range of applications.

1. Introduction

An understanding of seasonal snow cover is integral to ecosystem management, as it impacts a range of ecosystem services, including water supply and availability, habitat availability for wildlife species, forest fire risk assessment, as well as human use of the landscape. Under a changing climate the timing and extent of seasonal snow cover is uncertain (Barnett and Adam, 2005). The global extent of land covered with snow has declined in the past 30 years (Derksen and Brown, 2012; Kunkel et al., 2016; Sturm et al., 2017), as well as the number of days per year that ground is snow-covered (Brown, 2000; Clow, 2010; Stewart et al., 2005). Trends toward earlier spring snow melt at high-latitudes have been correlated to both increases and decreases in forest carbon uptake (Winchell et al., 2016; Pulliainen et al., 2017), as well as disturbances to the seasonal behaviors of certain wildlife species, such as the denning patterns of grizzly bears in North America (Pigeon et al., 2016). The accurate mapping of the spatial extent of seasonal snow cover is therefore increasingly important to understand the effects of snow dynamics on anthropogenic and natural processes and how to prepare for, and manage, future climatic conditions.

Satellite based detection of snow dates back to the 1960's and has enabled the quantification of broad spatial and temporal variability in snow cover on a variety of scales (Dietz et al., 2012). The global coverage available from remote sensing technologies allows detection in remote areas, where in situ measurements may not be possible (Nolin, 2010). In addition, satellite observations in mountainous terrain

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https://doi.org/10.1016/j.rse.2018.07.029
Received 3 April 2018; Received in revised form 24 July 2018; Accepted 26 July 2018
Available online 02 August 2018

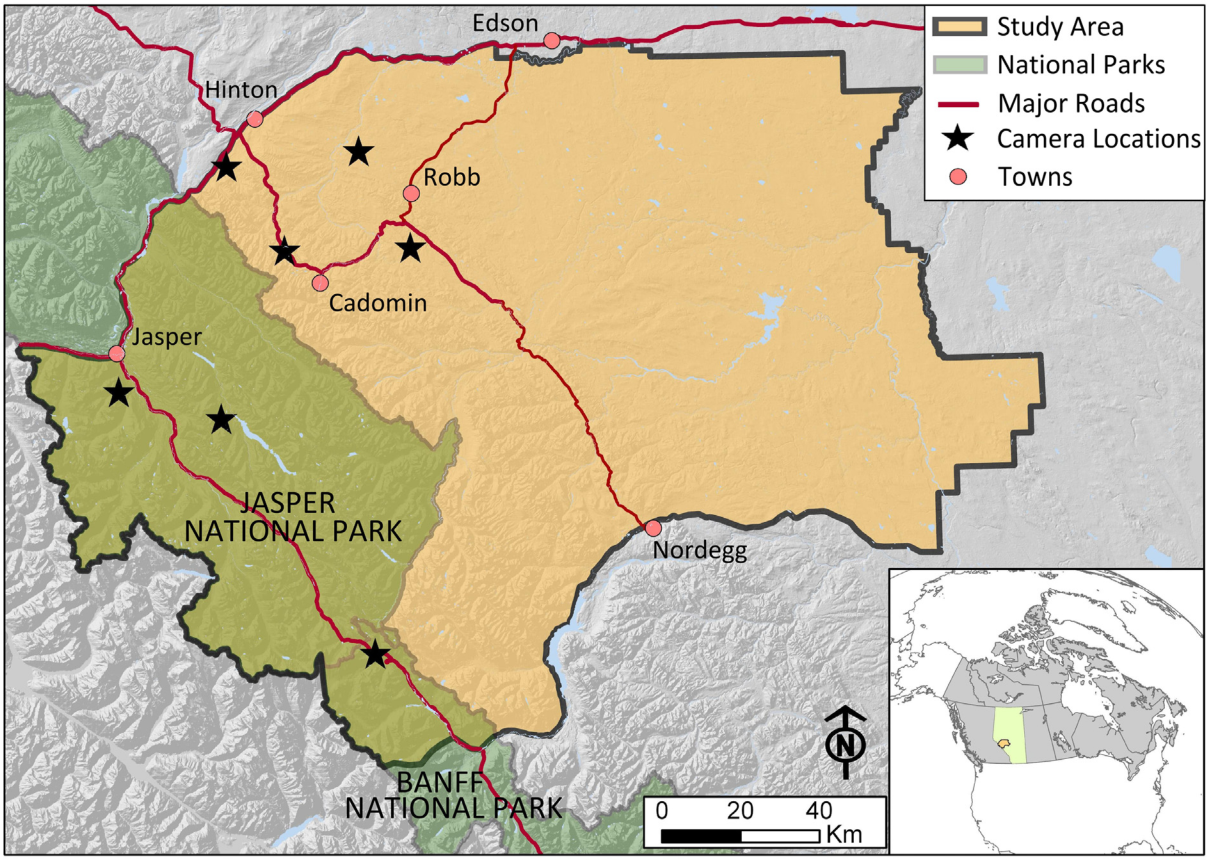

Fig. 1. A map of the Yellowhead region of Alberta.

provide key benefits where ground measurement networks often do not accurately capture the spatial variability of snow cover (Rittger et al., 2016).

Remote sensing technologies for snow cover assessment include Synthetic Aperture Radar (SAR), Light Detection and Ranging (LiDAR) and passive optical technologies (Dietz et al., 2012; Painter et al., 2016). Optical imagery provides reliable measurements of snow cover extent using visible wavelengths (Clifford, 2010) across a range of spatial and temporal resolutions (Dietz et al., 2012). The historical basis of snow covered area (SCA) mapping using optical technology is a "binary" map (Dozier, 1989), in which each pixel is designated as "snow covered" or "snow free" (Painter et al., 2009). More recent advances include fractional snow-covered area (fSCA) metrics, which are sub-pixel estimations of the percentage of snow cover determined to be in a pixel (Nolin, 2010). Snow products from optical sensors perform well in open, homogenous areas under ideal illumination and cloud-free conditions. Therefore forested regions and winter are major limitations to accurate snow information extraction leading to underestimation of SCA, since in forests the sensor can only register snow in canopy gaps (Liu et al., 2004) and during winter there is less solar reflectance and persistent cloud cover (Deeb et al., 2017). Previous studies have improved SCA estimates by adjusting values to account for forest transmissivity (Metsämäki et al., 2012) and the percentage of canopy cover (Rittger et al., 2013), however results have still shown underestimation of snow cover in forests. Static forest canopy adjustments are also limited in their assumption that snow cover under canopy mirrors snow cover visible in canopy gaps (Coons et al., 2014).

A 30-m resolution daily SCA product is desirable for certain hydrological and ecological applications, yet it is a challenging product to develop with spatial and temporal resolution trade-offs due to pixel size and sensor swath width. Daily 30-m SCA has been shown to reduce the error of snow water equivalent reconstruction (Durand et al., 2008), which provides important measurements of increasingly limited water resources. It is also a valuable tool to inform research on the relationship between wildlife behavior and snow dynamics. For example, grizzly bear den site selection and den entry and emergence dates are highly dependent on localized terrain and climatic variables (Pigeon et al., 2014; Schoen et al., 1987). No single remote sensing instrument is currently capable of producing such a high-resolution product, but a number of studies have demonstrated the ability to create 30-m daily SCA by fusing complementary optical datasets (Cristea et al., 2017; Czyzowska-Wisniewski et al., 2015; Durand et al., 2008; Li et al., 2015; Walters et al., 2014). Further work is needed to develop and validate a product that can be efficiently applied to large areas.

Dynamic Time Warping (DTW) is an algorithm used for time-normalization between two datasets. Originally developed for spoken word recognition (Sakoe and Chiba, 1978), it has been used as a data fusion approach to defining patterns between complementary time-series in remote sensing (Baumann et al., 2017; McConnell et al., 1991; Petitjean et al., 2012; Romani et al., 2010; Weber et al., 2012). DTW can be used to increase the temporal density of a multi-year historical data set, such as the Landsat satellite record, by shifting historical values in time to account for inter-annual variability. The shift is informed by rulesets generated from a temporally frequent complementary dataset, such as daily data from the Moderate Resolution Imaging Spectroradiometer (MODIS), which are used to normalize differences between years. Historical observations can then be re-used and applied (based on the rulesets) to the time-series of each year. Baumann et al. (2017) used a DTW approach on Landsat imagery from 2002 to 2012 to fit the phenology trend of each year, with yearly MODIS phenology curves driving the temporal adjustment of Landsat observations.

The aim of this research is to demonstrate and test a new methodology to derive a 30-m daily SCA product over a large mountainous and forested region in Western Canada. To do so we utilize the DTW