ISPRS Journal of Photogrammetry and Remote Sensing 144 (2018) 435–452

Contents lists available at ScienceDirect

ISPRS Journal of Photogrammetry and Remote Sensing

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

Comprehensive accuracy assessment of MODIS daily snow cover products and gap filling methods

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ARTICLE INFO

Keywords:
MODIS
Snow
Validation
SNOTEL

ABSTRACT

The accuracy of the standard Moderate Resolution Imaging Spectroradiometer (MODIS) daily snow cover products (Collection 5) and several of the most common and computationally frugal gap-filling methods were validated using 12 years of daily observations from over 800 Snow Telemetry (SNOTEL) stations. While several factors affect snow cover accuracy to some extent, the largest controls are associated with land cover type; accuracy fell from the maximum in croplands (94.9%) to the minimum for observations with a land cover type of water (79.5%). The second largest impact on accuracy is attributed to the changes in solar zenith angle, where accuracy decreased from a maximum of ~96% at 42° to a minimum of ~84% at 58°. Based on the results of this work, the highest accuracy binary daily snow cover dataset can be achieved by reclassifying the fractional snow band using a no-snow/snow threshold of 10 from the MODIS Terra sensor. Gap-filling is best accomplished by a temporal filter on the same dataset, and the window length depends on the desired completeness of the final dataset and the amount of missing values in the area of interest. Decreases in accuracy caused by this gap-filling method taper off after 7 days. Therefore, if a larger temporal window is needed to adequately fill in a time series it is best to extend the window to the largest gap present.

1. Introduction

Snow cover plays a pivotal role in global water and energy budgets and can be a significant economic benefit or detriment depending on when and where it falls. Its presence or absence has significant bearing on the nature and magnitude of fluxes within the water cycle, and the snow cover state can vary quite drastically in both time and space. To quantify the current and past state of the cryosphere in a global context, remote sensing offers a practical means to do so. Of the available instruments, the Moderate Resolution Imaging Spectroradiometer (MODIS) instruments on the Aqua and Terra satellites are uniquely suited to this task due in parts to their duality, comparably high spatial resolution of 500 m, global coverage, and high temporal resolution of approximately-one day in most snow-covered regions.

To discriminate between snow and no snow land cover states, the MODIS daily snow product uses bands 4 (0.545–0.565 μm) and 6 (1.628–1.652 μm) to calculate a Normalized Difference Snow Index (NDSI). The band 6 failure on MODIS Aqua satellite results in the use of band 7 (2.105–2.155 μm) in the MYD products in Collection 5. In addition to NDSI, a normalized difference vegetation index is also used, and a variety of other thresholds and masks are applied and are described in the product user's guide (Riggs et al., 2006). For simplicity, we can reduce the factors which affect the accuracy of these snow cover products into illumination angle and reflectance of the surface. These include the fractional snow cover of a pixel, the land cover state, the temporal variation of these properties at yearly and monthly scales, and sun-sensor geometry.

Previous studies have examined these factors in some detail. As of July 2016, the MOD10 products have been validated to stage 2, meaning its accuracy has been validated across a representative number of spatial and temporal domains using other reference data ("EOS Val Status for Snow Cover/Sea Ice: MOD10/29," n.d.). Efforts from the community place the traditional accuracy of MODIS snow cover products between 85 and 95% depending on the study area, season, and method of validation (Ault et al., 2006; Bitner et al., 2002; Déry et al., 2005; Gao et al., 2011; Hall and Riggs, 2007; Klein and Barnett, 2003; Maurer et al., 2003; Parajka and Blöschl, 2006). However, in order to push the collection into stage 3 validation, the quantification of the uncertainties in these accuracies need to be determined.

As is the case with many remote sensing products, one of the primary drawbacks of the MODIS sensor arises from its inability to identify the land cover state through cloud cover, which can at any given time cover more than 70% of the globe (Wylie et al., 2005). Combined with other conditions that interfere with the detection of snow cover (e.g.

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https://doi.org/10.1016/j.isprsjprs.2018.08.004
Received 31 March 2018; Received in revised form 31 July 2018; Accepted 1 August 2018

night and detector malfunction), a snow cover time series for any given location may have many missed observations, or "gaps" which hinder the overall utility and accuracy of a timeseries of the product. For example, in this study more than half (52.6% for MODIS Terra) of the potential observations were lost due to missing observations.

To rectify these shortcomings, previous studies have employed a variety of cloud removal techniques to fill in those gaps. The most commonly used methodologies usually involve a combination of different MODIS sensors and the use of a temporal autocorrelation filter. The desire for a gap-filled dataset is so strong that the M*D10A1 collection 6 data products provide a gap-filled dataset that relies at least partially on temporal autocorrelation (Hall et al., 2010; Riggs et al., 2016). While these gap-filled datasets are often employed in studies, their accuracy is underexplored and, when reported, use just a handful of ground truth observations. This makes direct comparisons between these different methods difficult as it is unclear how the various gap-filled datasets compare either to each other, to the standard MODIS snow cover dataset, or to ground truth. See Appendix B for a summary table of previous validation efforts based on Table 9 from chapter 9 of *Multiscale Hydrologic Remote Sensing*. Underlying this gap filling process is the tradeoff between complexity and accuracy. Although more complex gap filling methods have been developed, for rapid data access platforms (such as Google Earth Engine or Amazon) have several M*D10 datasets preloaded into them), if the resources needed to generate such datasets create computational or methodological barriers for minimal gains, the cost to do so outweighs the benefits (Andreadis and Lettenmaier, 2006; Liang et al., 2008; Parajka et al., 2010; Thompson and Lees, 2014).

To address these deficiencies, this research undertakes a rigorous validation of the MODIS daily snow cover products, and several common gap-filling methods using 12 years of daily snow observations from 819 Snow Telemetry (SNOTEL) stations distributed across the western United States and Alaska with more than 3.2 million potential ground truth observations. With such a large and varied validation dataset, this work presents one of the largest and most comprehensive validation of MODIS Terra and Aqua daily snow cover products (M*D10A1 Collection 5) and the most commonly employed gap-filling methods.

2. Data

2.1. Snow cover data

The snow cover data used for this validation comes from the MODIS daily snow cover products M*D10A1 (Collection 5) between 2002/10/01 and 2014/09/30. Daily MODIS values at the pixels which contain SNOTEL stations are extracted and, when applicable, reclassified based on a threshold determined experimentally (see Section 4.1). For the purposes of this study, water and ocean observations are counted as a valid land cover observation, and ice is considered snow. More details about the MODIS snow cover datasets can be found in the product user's guide to Collection 5 (Riggs et al., 2006).

2.2. Ground snow observations

The ground truth dataset used in this research comes from the SNOTEL network which consists of over 800 sites distributed across 12 states in the western United States including Alaska, shown in Fig. 1. These stations are generally located in high elevation and remote watersheds and collect data which is used for a variety of purposes including flood prediction and climatic research. Among other hydrologic variables, these sites measure daily snow water equivalents (SWE), reported daily with 0.1 in. precision ("NRCS National Water and Climate Center | Home", n.d.). The use of SNOTEL SWE as a surrogate for snow depth is less than ideal. This is because MODIS only measures the presence or absence of snow; radiometrically a snowpack of 10-meters depth is almost identical to a 1-meter snowpack. Additionally, at the scale of the MODIS pixel (500 m), the snow pillow is effectively a point. These sites are also located in open, flat clearings in hydrologically relevant catchments which may not necessarily be representative of the pixel MODIS detects. Nevertheless, this is the most widely used means of validating MODIS snow cover products, and the SWE measurement is more reliable than snow depth sensor (Bitner et al., 2002; Klein and Barnett, 2003; Parajka and Blöschl, 2006). The data was retrieved from the United States Department of Agriculture's Natural Resources Conservation Services website ("NRCS National Water and Climate Center | SNOTEL Data & Products," n.d.) for all available SNOTEL stations between 2002/10/01 and 2014/9/30. In Fig. 1, several latitude bands are defined for use later in the validation. The mean length of polar night is also included to aid users in determining how a location is affected by this persistent, gap-inducing condition.

2.3. Land cover data

To examine the impact of land cover type on snow cover accuracy, observations were given a land cover classification based on the International Geosphere-Biosphere Programme classification as provided by the MODIS MCD12Q1 dataset produced yearly for 2001–2012. Land cover types were retrieved for the SNOTEL stations and joined to the snow cover observations based on the calendar year that covered the bulk of a hydrologic year (October 1 to September 30 of the next year), i.e. snow cover observations from hydrological year 2003 (2002/10/01–2003/09/30) were assumed to be associated with the land cover types of calendar year of 2003 (2003/01/01–2003/12/31). The land cover classification scheme, as well as their count percentage with the validation observations, are shown in Table 1. More information on MCDQ12Q1 can be found in the user's guide ("MCD12C1 | LP DAAC :: NASA Land Data Products and Services," n.d.) and in Friedl et al. (2010).

2.4. Sensor data

To understand the impact of sensor-sun geometry on snow cover accuracy, the MODIS daily surface reflectance datasets (M*D09GA), which contain sensor properties, was extracted and joined with the daily snow cover data (M*D10A1). More on the sensor property data can be found in the product user's guide (Vermote et al., 2011).

3. Methods

3.1. Cloud removal techniques

To assess the accuracy of the standard daily snow cover products, their combinations, and various gap-filling methods, three levels of datasets were designated ordered roughly on the amount of processing required to create them.

Level 1 datasets are comprised of the products from a single MODIS sensor, either Terra or Aqua, and include the standard Snow-Cover-Daily-Tile band (hereafter referred to as MOD and MYD respectively), or a product that combines the Fractional-Snow-Cover band with the Snow-Cover-Daily-Tile band (hereafter referred to as F-MOD and F-MYD respectively). To create F-M*D products, the Fractional-Snow-Cover band is reclassified into a no-snow/snow/missing state based on an experimentally determined threshold (see Section 4.1). Preference is given to the Fractional-Snow-Cover band and the value in the Snow-Cover-Daily-Tile band is carried through only when the Fractional-Snow-Cover band has a missing value, but the Snow-Cover-Daily-Tile band has a valid value. This is a rare occurrence, happening just 855 times within the timeframe, and the accuracy results reported for F-M*D products would be virtually identical to a dataset created from the fractional band alone. Therefore, this step may be skipped if desired.

Level 2 datasets include the combinations of level 1 datasets from